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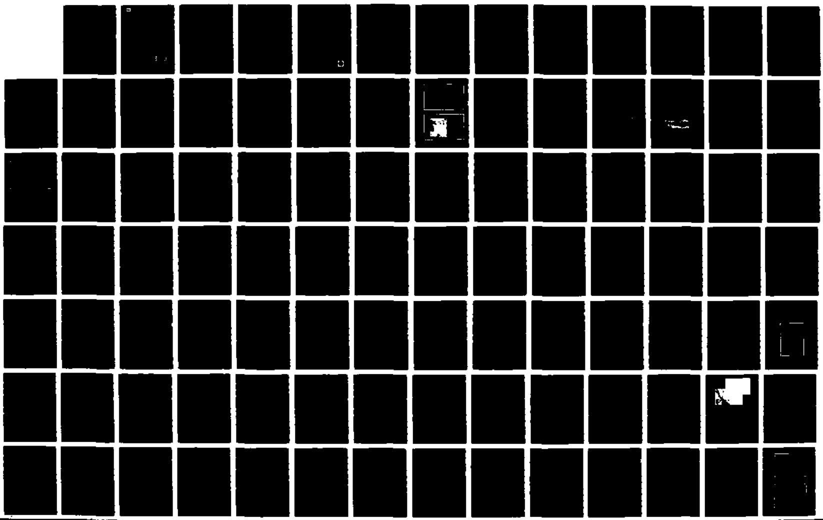

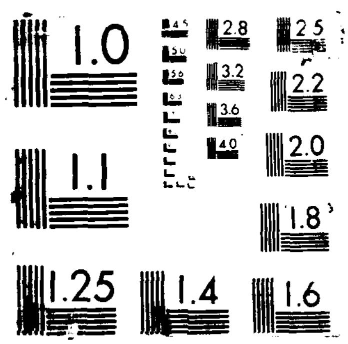
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US Army Corps
of Engineers

The Hydrologic
Engineering Center

Remote Sensing Technologies

and

Spatial Data Applications

Research Document No. 29

December 1987

Remote Sensing Technologies

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Prepared for

The Hydrologic Engineering Center

by

The Earth Satellite Corporation

December 1987

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FOREWORD

This document was prepared as part of the efforts in the Hydrologic Engineering Center's, HEC, R&D Work Unit: Remote Sensing and Spatial Data Applications. The views expressed in the document are those of the Earth Satellite Corporation, as guided by HEC's general research and development interests. This investigation of remote sensing applications to hydrology was not limited to existing capabilities. Many potential capabilities are suggested although the practical means to accomplish them may not be readily available at this time.

The discussion of various technical products/capabilities is not meant as an endorsement/criticism thereof. This is a rapidly growing industry and capabilities are ever changing. Up-to-date information should be sought from the various suppliers.

HEC staff involved in this project were David Goldman, Darryl Davis, and Arlen Feldman. Mr. Bill Eichert was Director of the HEC during this project.

REMOTE SENSING TECHNOLOGIES AND SPATIAL DATA APPLICATIONS RELEVANT TO HEC PROGRAMS AND MISSION

FINAL REPORT

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PREFACE

The Hydrologic Engineering Center (HEC), U.S. Army Corps of Engineers, issued a contract with Earth Satellite Corporation (EarthSat) on October 6, 1986, to conduct a study addressing remote sensing technologies and spatial data applications relevant to HEC programs and mission. The study involved a series of related tasks as follows:

1. Investigate Emerging Remote Sensing Capabilities;
2. Analyze Computing Environments; and
3. Review Improvements of Spatial Data Analysis Methods.

Owing to the diversity of these tasks, the talents and expertise of a number of team experts was utilized. The entire report was under the overall direction of Mr. William Brooner, Earth Satellite Corporation (EarthSat) who also prepared Appendix B. Mr. Michael Place of EarthSat, prepared the Digital Image Processing and the Evaluation of PC-Based Image Processing/GIS Systems sections. Dr. Robert Ragan of the University of Maryland produced the hydrologic modeling studies. Mr. Donald Wiesnet, Satellite Hydrology, Inc., contributed to portions on snow cover, soil moisture, and Quick Response Monitoring on Floods, and together with Mr. Earl Merritt of EarthSat, produced the Real Time Estimates of Precipitation and Snow Cover: An Evaluation of HEC options. Mr. Morris Deutsch of Satellite Hydrology, Inc., prepared Appendix A. Ms. Coeta Withgott of EarthSat prepared the typescript.

The report has been greatly strengthened by the guidance and oversight of the Corps of Engineer's COTR, Mr. Arlen D. Feldman, who gave freely of himself to clarify and specify the needs and goals of the Hydrologic Engineering Center as they relate to this contract. We wish to express our appreciation also to Dr. David Goldman of HEC whose insightful review of our progress report was most helpful in sharpening our focus on HEC's immediate needs in remote sensing.

ROLE OF REMOTE SENSING AND INFORMATION SYSTEMS IN THE OPERATION OF HEC HYDROLOGIC AND FLOOD DAMAGE MODELS

1.0 *INTRODUCTION*

Access to accurate and timely information is a cornerstone in any decision making process. In today's society with multiple, often conflicting, demands on the use of a resource, it is mandatory that decision makers interface their information with sophisticated models that can realistically simulate the consequences of the array of strategies available to them. In the area of water resources, the Hydrologic Engineering Center (HEC) is recognized for its leadership in defining information requirements and providing simulation models used to support the decision making process, not only for the Corps of Engineers, but for organizations throughout the world.

Developing the information required for water resource decision making is a tedious, time-consuming and expensive task requiring a significant commitment of skilled personnel. The launch of the first Landsat satellite in 1972 was seen by many as an opportunity to revolutionize the collection and management of information for water resources. HEC was one of the first organizations to seriously investigate the potential of Landsat for water-related problems. These investigations quickly revealed the interrelationship between this new digital format data plane and a computer-centered technology that would interface Landsat data with other data sets and then manage them for subsequent use in models. Thus, as part of its work related to overall remote sensing applications, HEC was one of the first organizations to develop a Geographic Information System (GIS) that was called Spatial Analysis Methodology (SAM). This research led to the conclusion by Cermak, Feldman and Webb (1979) that Landsat MSS remote-sensing-derived land cover information was sufficiently accurate to apply Snyder's unit hydrograph model with percent of imperviousness and the SCS curve number and lag method. Several HEC publications on grid-cell data bases became very important references for integrating Landsat data sets into GIS (e.g., Ford, Meyer and Algazi, 1985; USACE, 1978; USACE, 1979).

Despite the work of HEC and many other organizations, satellite remote sensing to support routine hydrologic investigations has not realized its potential. Part of the problem has been with the perceived limitations of the 80-meter or 30-meter resolution of the Landsat systems. Until the introduction of the PC-based image processing systems, a second problem has been ready access to the specialized equipment needed for interpretation and management of the satellite data. Perhaps an equally important problem has been in the management of Landsat data. Proponents of Landsat did not fully recognize that land cover was only one of several data sets required for the modeling of a watershed. Even though land cover could be defined in a matter of hours, it still required many weeks to develop the soils, topography and socioeconomic information before the land cover could be "overlain" on the other data sets. Thus, there has been little incentive to develop expertise in Landsat land cover utilization. The critical missing ele-

ment needed for success has been an efficient, readily available, method for merging and managing the numerous data sets - what we currently call a "user-friendly" GIS.

Because of the tremendous changes created by the development of powerful, inexpensive personal computers, there are a number of GIS packages that provide many of the original HEC-SAM capabilities on desk-top workstations. These personal computer workstations can operate as "stand-alone" systems that allow the individual to literally take a 24" x 36" digitizing tablet off the wall and quickly develop and manage the data sets required for an intermediate-sized watershed. At the same time, this personal computer workstation can be networked with remote computing capabilities to become a component in a regional system. *Figure 1.1* is a schematic that shows the concept of the workstation having access to both specialized image-processing capabilities and the power and storage offered by conventional mainframe or super computers. This workstation capability is presently available and can be a major driver in opening the door to widespread use of the benefits offered by digital format remote sensing. These workstations are further discussed in detail in a subsequent GIS systems section of this report.

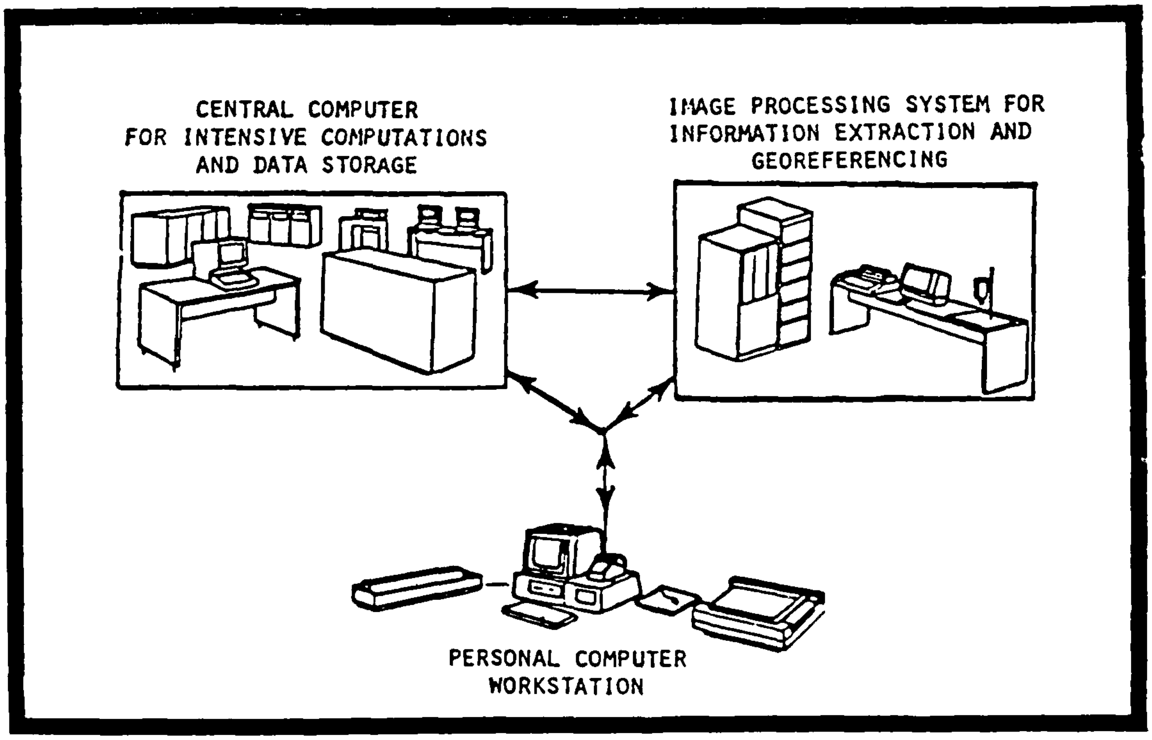


Figure 1.1. Network Structure for Remote Sensing Based Hydrologic Analyses

New satellite and aircraft digital format remote-sensing systems that are now available overcome many of the 80-meter resolution problems of the Landsat Multispectral Scanner (MSS) imagery. There are now satellites with 10-, 20- and 30-meter resolution, systems that provide detail that is sufficient for a large array of hydrologic analyses. When coupled with aircraft and ground-based sampling programs, the high-resolution satellite images can become very important sources of information. Fortunately, because of the current powers of GIS and digital-format remote sensing, we are at a point where the hydrologic community can really begin to integrate the array of data sources available. The term "fortunately" is used because the profession is at a point where fast, theoretically sound, accurate modeling is imperative. The Corps of Engineers is moving into a mode of operation that requires real-time assessments of the economic consequences of decisions that must be made during the passage of a flood. These decisions must be based on a thorough, quantitative understanding of the watershed, the reservoirs and the floodplains. The systems needed to translate these data into the required information are available. The information systems to allow the hydrologists to simulate the consequences of a set of alternate strategies are also available.

The following sections focus on the role of remote sensing and information management systems in the operation of HEC hydrologic and flood damage models. The first two sections are brief overviews on the capabilities of sensors and information systems as they relate specifically to hydrology. Detailed discussions of these elements follow later in the report. Next, the roles of remote sensing and information systems as they relate to specific tasks involving HEC-1, HEC1-F, DWOPER, HEC-2, SID, DAMCAL and EAD are discussed along with the role of remote sensing to specific selected hydrologic engineering/planning tasks.

Considerable progress has been made in digital format remote sensing since the 1972 launch of the first Landsat. New systems are in orbit and digital sensors are becoming more widely used in aircraft. The real and perceived disadvantages of the 80-meter resolution on Landsat MSS are no longer as critical because of the later launches of 10-, 20- and 30-meter resolution systems. Indeed, hydrologists are now looking seriously at the possible information that can be provided by the 1-km resolution AVHRR and the global scale GOES systems. While the 10- to 30-meter resolution systems require more sophistication for computer-aided interpretation, their level of detail allows conventional photointerpretation and direct manual digitizing for many hydrologic applications (*Table 1.1*).

TABLE 1.1: SELECTED HYDROLOGIC PARAMETERS CURRENTLY OR POTENTIALLY AVAILABLE FROM REMOTE SENSING

PLATFORM	SENSOR	SELECTED HYDROLOGIC RELATED PARAMETERS
Landsat	30-meter TM or 80-meter MSS	o Land Use/Land Cover o Impervious Surfaces o Surface Water & Drainage Networks o Snow and Ice Cover o Vegetation Species, Extent, and Characteristics o Ground Water Recharge & Discharge Areas
SPOT	10-meter Panchromatic	o Land Use/Land Cover, with Inter-Urban Detail and Drainage
	20-meter Spectral	o Land Use/Land Cover o Spatial Variability of Drainage Units
NOAA Polar Orbitor	AVHRR	o Vegetation index o Biomass o Canopy Temperature o Water temperature o Albedo o Surface water areal extent o Ice and snow cover (regional) o Drainage networks (regional)
GOES	VISSR	o Qualitative Precipitation Distributions o Snow Cover o Cloud Cover and Movement o Solar Radiation o Surface and Canopy Temperature o Albedo o High Altitude Winds
DMSP	Operational Leniscan System (OLS)	o Canopy temperature o Water temperature o Broad band albedo o Ice and snow cover o Drainage networks o Surface water areal extent
	Special Sensor M/T - A passive microwave temperature sounder (SSM/T-1) (SSM/T-2)	A 7-channel scanning passive microwave radiometer (50-60 GH2) used for temperature profiling from earth's surface to above 30 km.
	Special Sensor C (SSC) Snow/Cloud Discriminator	- Distinguishes snow from clouds
	Special Sensor M/I (SSM/I)	o Location, extent and intensity of precipitation
	Microwave Environmental Sensor System	o Soil moisture, sea ice and lake ice morphology
Aircraft	Laser Mapping	o Elevations and Channel Cross Sections
	Gamma-ray	o Water equivalent of snow and soil moisture
Future	Microwave or IR	o Soil Moisture o Water Equivalency of Snow o Precipitation o Soil Hydraulic Properties

2.0 *OVERVIEW OF INFORMATION SYSTEMS FOR HYDROLOGIC ANALYSES*

The term "Information Systems," in the present context, relates to the assembly, storage, management, translation and application of information for hydrology-related analyses. The emphasis is on the GIS as a component for modeling and defining distribution conditions spatially. Sound information systems are critical for accessing and interpreting data-collection systems or archived data sets. The role of these elements in an information system is included in the discussion of each modeling or analysis task in the following sections.

Before discussing the roles of remote sensing and information systems as they relate to specific tasks involving HEC models, it is appropriate to establish some of the current capabilities of GIS, especially those designed for personal computers. The capabilities are impressive when viewed from the perspective that many of the capabilities were not even available on mainframes just a few years ago. The capabilities of one specific system will be used for illustration. However, it is emphasized that these capabilities are available on a number of different systems. ***Figure 2.1*** is a flow chart that illustrates the structure of an interfaced GIS and Expert System for hydrologic analysis. The upper portion is the conventional GIS configuration used by most systems. The lower portion is an indication of the structure that will be used in the future as we evolve toward artificial intelligence and expert systems. The GIS block of Figure 2.1 can now be fully implemented on an array of off-the-shelf personal computers as illustrated by ***Figure 2.2***. Most of these personal computers have excellent color graphics and large memories and disk storage. The simple addition of a digitizing tablet through one of the communications ports produces a very flexible workstation that can either stand alone or be networked as in Figure 1.1.

Because the reader is assumed to be familiar with the capabilities of SAM (with respect to interfacing with models and managing the data sets), these aspects of a GIS will not be discussed here. Instead, the specialized capabilities will be presented in order to support some of the discussions in the following task-related sections.

Region growing evolved from some of the image-processing research associated with satellite-data processing and is an important component in a hydrology-oriented GIS where a series of point measurements must be translated into a spatial distribution of values referenced to grid cells or other geographic locators. Key uses of region growing in hydrology involve spatial distribution of rainfall and watershed topography. For example, the hydrologist can digitize an isohyetal map, and then use region growing to interpolate the rainfall values between the isohyets to obtain the spatially distributed rainfall for every cell in the watershed. ***Figures 2.3A*** and ***2.3B*** illustrate the results of region growing on isohyets. Figure 2.3A is a line printer copy of a color CRT display of an isohyetal map. Figure 2.3B indicates the distribution of individual cell rainfall estimates with areas of 4-8 inches, 8-16 inches and 16-25 inches in the mountains west of Denver highlighted by shading.

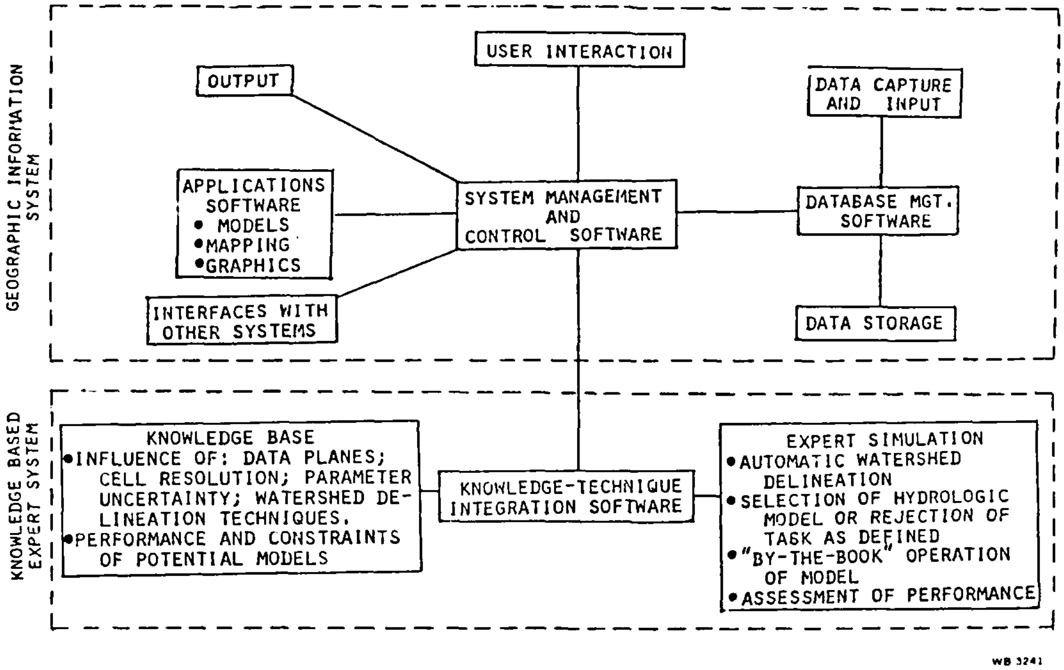


FIGURE 2.1. GIS-expert system interaction for hydrologic analysis.

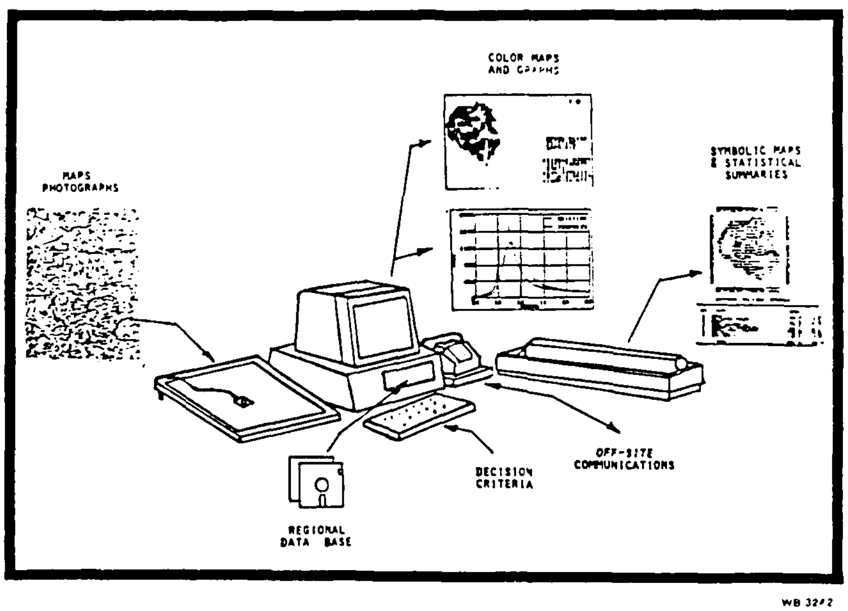


FIGURE 2.2. Microcomputer work station for land and water resource analysis.

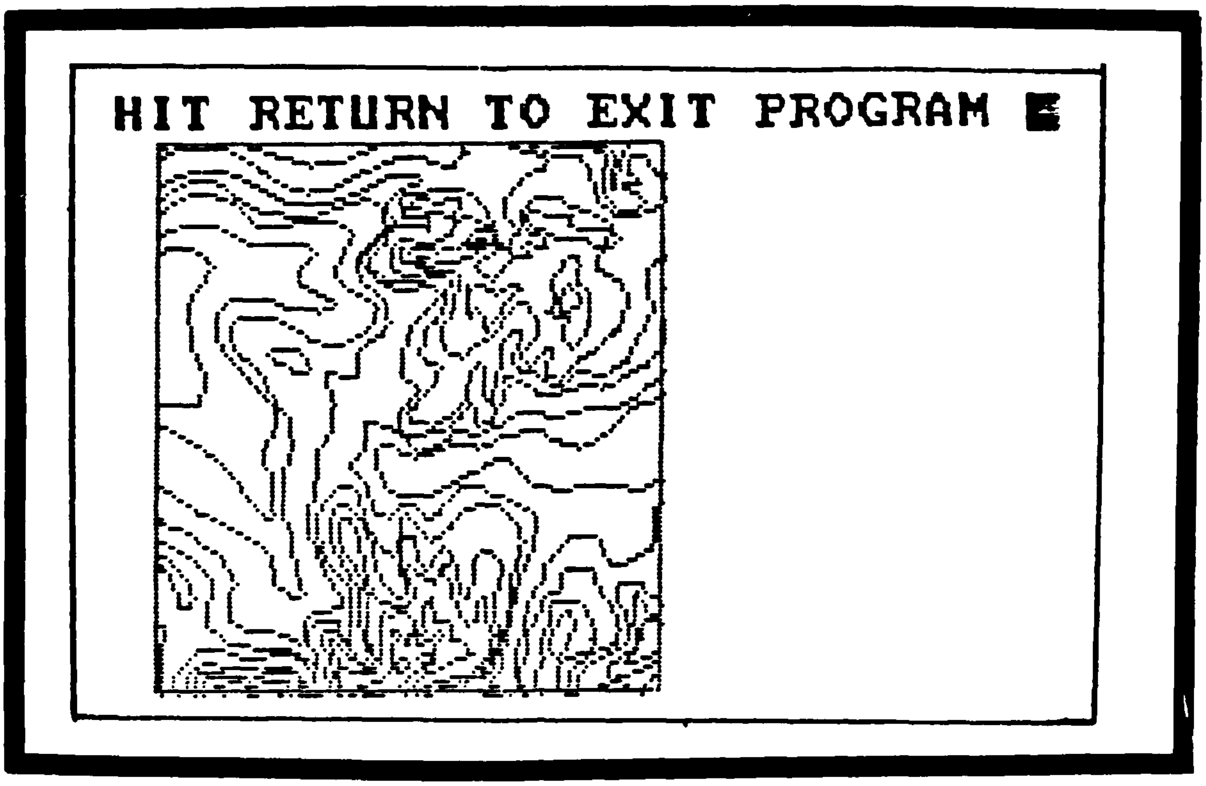


FIGURE 2.3A. Dot matrix printer copy of color CRT display of isohyetal map.

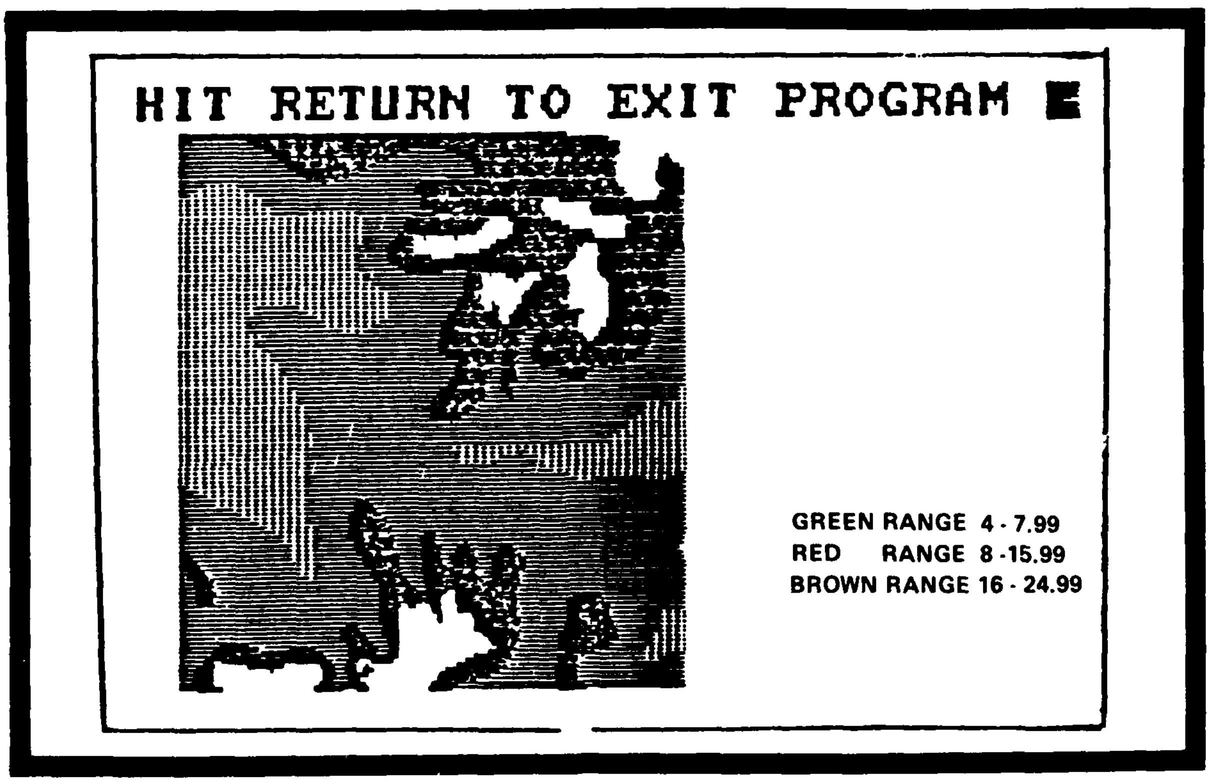


FIGURE 2.3B. Dot Matrix printer copy of color CRT display showing ranges of precipitation in locations isolated from isohyetal map through region techniques applied to figure 2.3A.

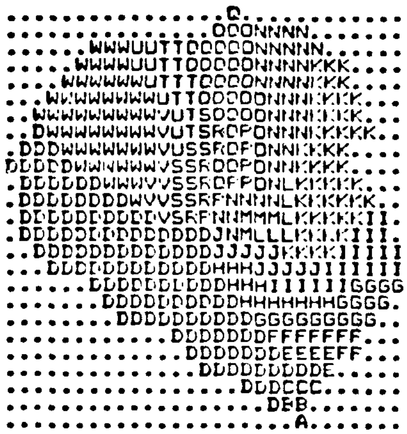
Figures 2.4-2.8 illustrate the use of region growing on digitized isopleths to isolate an overall watershed as well as its subwatersheds. Figures 2.7 and 2.8, for example, show the subarea draining into a specific reach along a stream and the area above that point. This watershed segmentation also defines the flow network and allows the development of time-area curves -- such as shown in *Figure 2.9* -- that are required for the Clark option of HEC-1.

A good GIS for hydrologic applications must also be able to manage several data planes at a time that will have differing resolutions. For example, the general operation of the GIS may be on a grid-cell data base of 1 to 10 acres. Still, the system must provide the opportunity to work in local areas at much higher resolutions. *Figures 2.10A* and 2.10B illustrate the merging of elevation and land cover data sets having resolutions of approximately 0.1 acres in an overall data base that was made up of 4.54 acre cells.

To properly use capabilities such as those outlined above, the hydrologist must not only understand their mechanics, but also their performance in terms of information quality. The hydrologist must be able to quantify the role of cell size or inaccuracies in the data relative to the decisions that will be based on the results. The basis for such an ability must come from sensitivity analyses that are conducted in an arena that closely approximates the conditions anticipated in the field.

The role of cell size in a GIS is a frequently debated issue. In some situations, a cell of 10 acres or even larger can be completely adequate relative to the decision to be supported. In other situations, it may be necessary to develop information cells for areas of a fraction of an acre. The performance of the region-growing algorithm described above is quite sensitive to the number of cells within a watershed which, in turn, influences cell size because of the watershed sizes involved in a study. *Figure 2.11* illustrates the agreement between manually delineated watersheds and those grown automatically from a digital terrain data set. Thus, if automatic watershed delineation and segmentation is to be integrated into Corps of Engineer operations, users will have to be trained to appreciate this type of performance.

Sensor resolution and similarity of cell size in a GIS, obviously influence the detail of a land cover data plane. Thus, the quality of a decision can be seriously impacted. Sensitivity studies must be conducted to allow the largest data cell to be adopted in order to minimize the costs of data collection and input and the operation of the GIS. *Figure 2.12* illustrates the effect of cell size on the behavior of the SCS Curve Number. This figure is for a land cover distribution that is representative of one particular situation. The sensitivities change for different land-cover patterns. Thus, this type of analysis would have to be repeated several times in order to develop sensitivities that are applicable for the variety of conditions encountered by the Corps of Engineers. Such sensitivity analyses are conducted on synthetic land-cover distributions generated by computer that can be set to well-defined spatial distributions.



AREA IN ACRES = 2088.45

AREA IN SQ. MI = 3.263203

FIGURE 2.4. Watershed grown from a downstream cell.

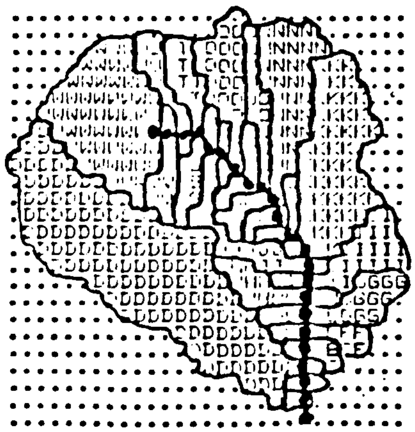


FIGURE 2.5. Sub-watersheds--Upper Sligo Creek.

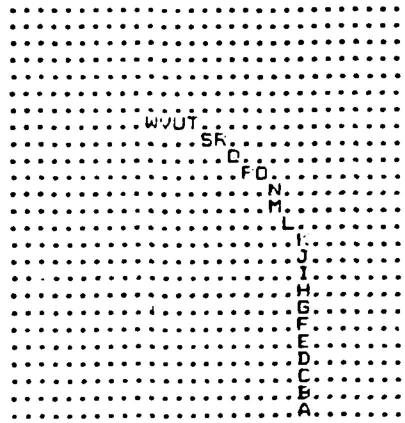
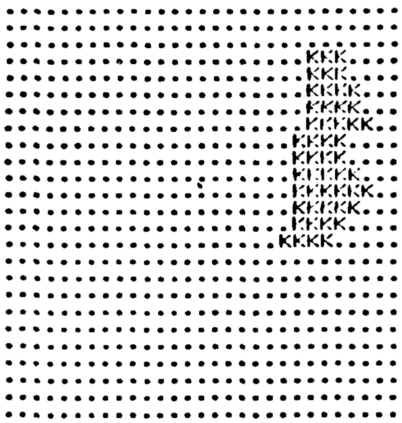


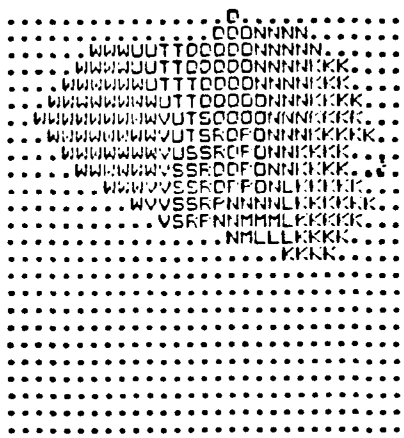
FIGURE 2.6. Stream location--Upper Sligo Creek.



AREA IN ACRES = 234.09

AREA IN SQ. MI = .3657656

FIGURE 2.7. Local area draining into node 11.

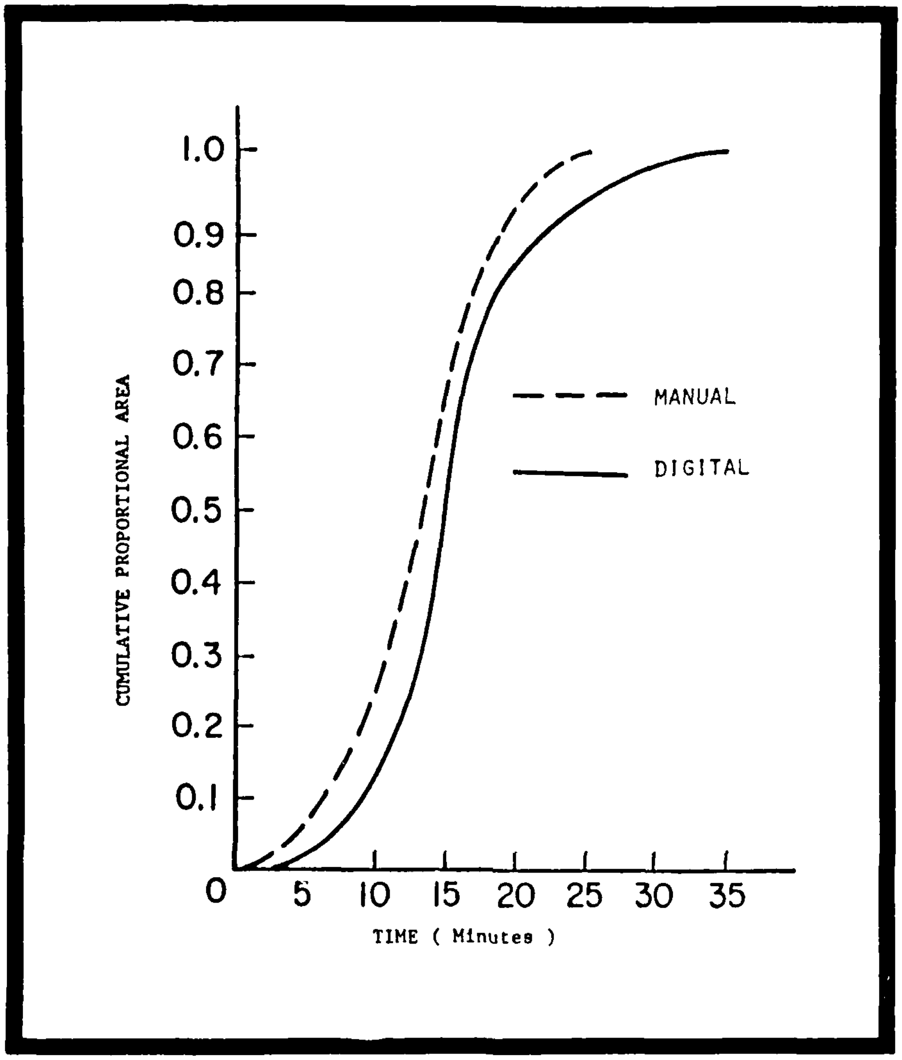


AREA IN ACRES = 1115.37

AREA IN SQ. MI = 1.742765

FIGURE 2.8. Watershed above node 11.

WB 3244



WB 3245

FIGURE 2.9. Comparison between a manually computed and a digitally synthesized Time-Area curve for Treynor Watershed, Iowa.

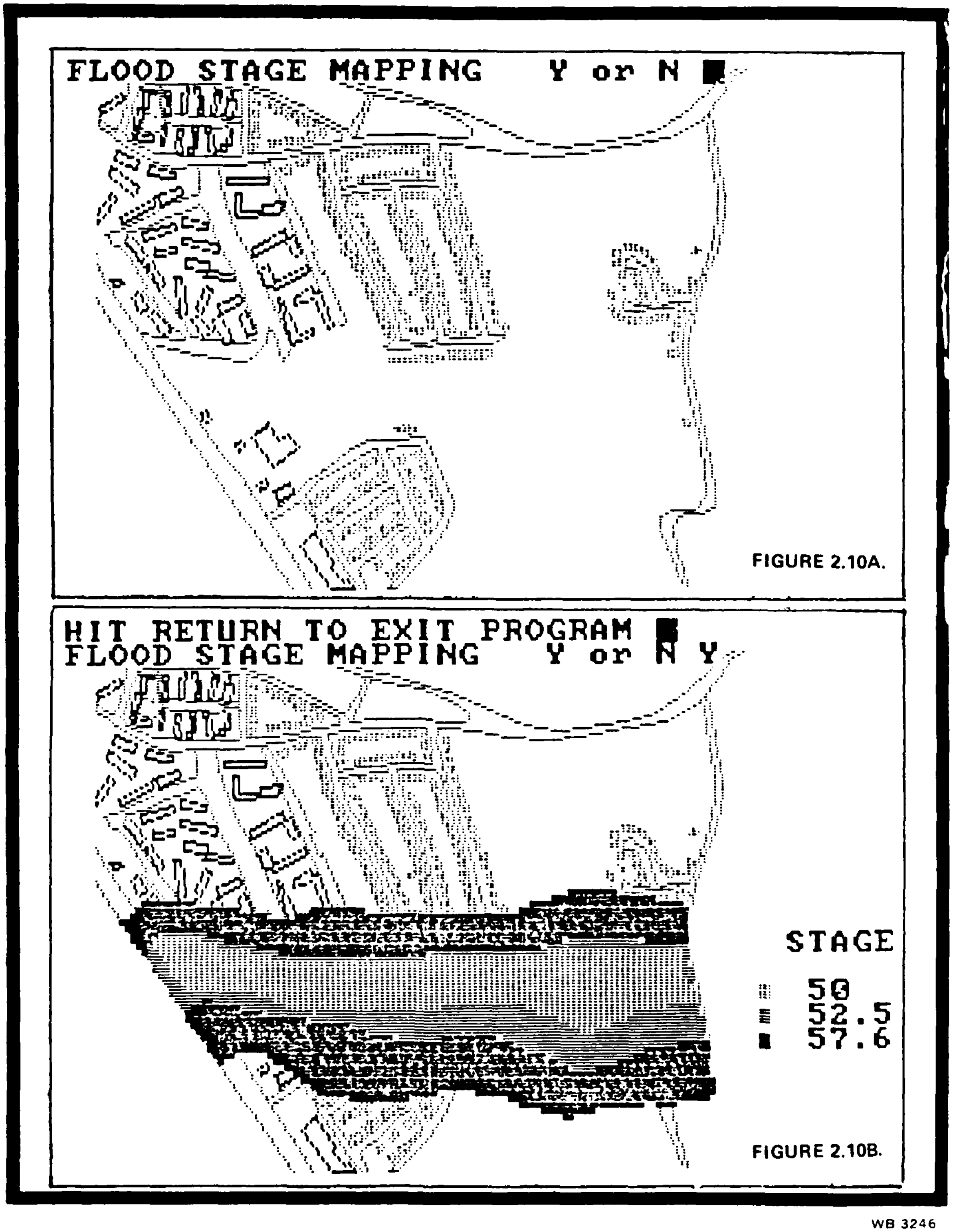


FIGURE 2.10A. Dot matrix printer copy of color CRT display showing features digitized from 1inch=40feet aerial photography as displayed by PC CGA.

FIGURE 2.10B. Dot matrix printer copy of color CRT display showing an overlay of digital elevation and flood stage data to delineate areas innundated by three discharges.

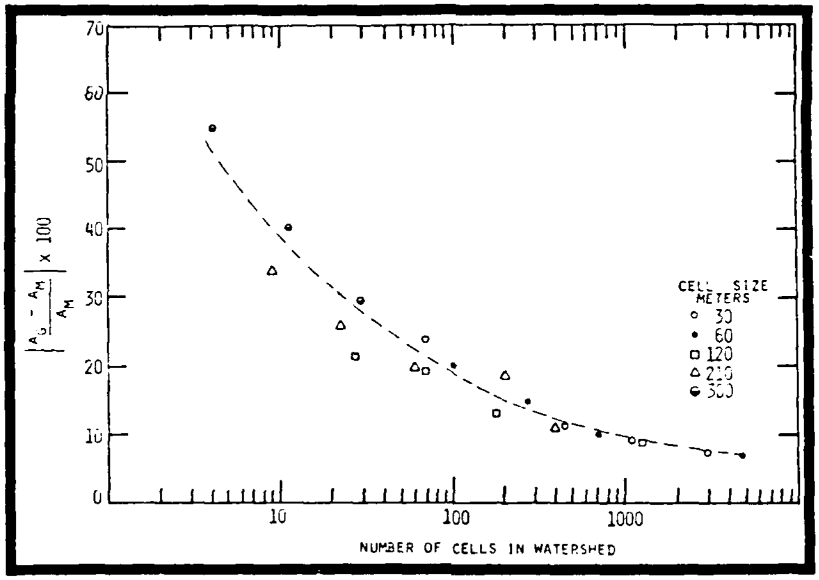


FIGURE 2.11. Expected differences in watershed areas produced by automatic region growing (A_G), and manual delineation (A_M), by a human expert.

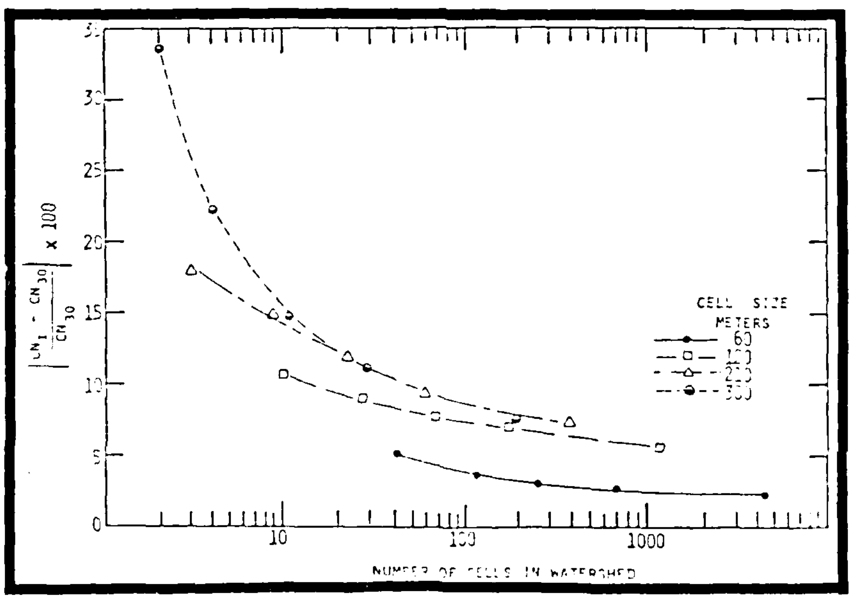
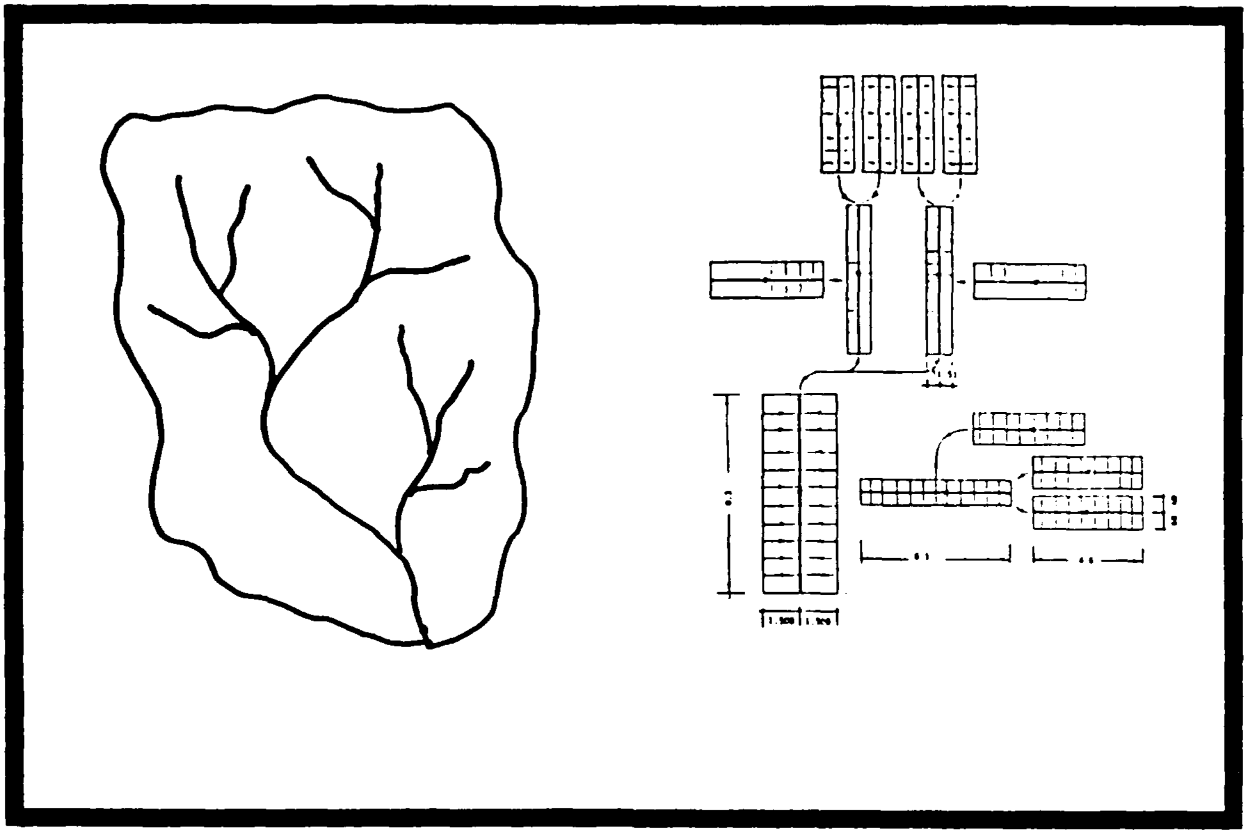


FIGURE 2.12. Expected differences between SCS curve number estimated with indicated resolution obtained with a sensor having 30 meter resolution.

A very critical problem for the Corps of Engineers centers on the quality of information in streams and floodplains. Because of increased computer power, the use of very sophisticated models to simulate river hydraulics is a realistic option. However, if the potential of these more powerful models is to be realized, they require significantly more information than those that have been in use for many years. Water-surface profiles and unsteady flow simulations using the complete differential forms of the continuity and momentum equations require large numbers of channel cross sections, slopes and the spatial distribution of roughness coefficients. If these data are inaccurate or of insufficient detail, it may be a complete waste of resources to apply a sophisticated channel hydraulics model. The role of uncertainty in the performance of a de Saint Venant routing model is illustrated by ***Figures 2.13 and 2.14***. As in cell size, the role of uncertainity is influenced by the spatial structure of the channel. Figure 2.13 is a schematic of the channel network investigated and the system representation used in the computer analyses. The structure of the routing model is closely related to DWOPER. The Table of ***Figure 2.14A*** indicates that the model is quite robust and can provide reasonable estimates of flows at a watershed outlet despite rather large errors in cross-section or roughness at individual stations if these errors are randomly distributed about a good estimate of the true means. However, it must be emphasized that the details of the water surface profiles along the channel could exhibit large errors. ***Figures 2.14B and 2.14C***, on the other hand, show rather large departures when the cross-section or roughness errors are biased above or below the true means of the stream network. It should be pointed out that the relatively small errors in the depths result from the use of depth hydrographs as upstream boundary conditions.

The lesson from Figures 2.14B and 2.14C is that the potential for improved results provided by a dynamic wave model may not be realized unless we have sound estimates of the flow geometry and the roughness parameters. However, the table of Figure 2.14A indicates that very good outlet hydrographs can be computed with this type of model if we have good estimates of the means along the stream network even though there may be randomly distributed errors at individual stations.

This type of sensitivity analysis is very important when one considers the use of one of these newer models. We must know the accuracy level requirements of the input parameters and the consequences of errors. If the accuracy requirements are understood, then remote sensing capabilities can be assessed to determine if existing sensor systems can meet the requirements. For example, if flood flow moving along a stream network extends well into the floodplain, it is possible that LIDAR could be of value in providing cross section information.



WB 3248

FIGURE 2.13. Schematic representation of the second synthetic basin as was used in the computer code.

Percentage error ε	Unbiased Change in Cross-Section						Unbiased Change in Manning's $\bar{n}$					
	Peak Discharge		Time to Peak		Max. Depth		Peak Discharge		Time to Peak		Max. Depth	
	q_p cfs	% error	t_p hrs	% error	Ymax ft	% error	q_p cfs	% error	t_p hrs	% error	Ymax ft	% error
0	5506	0	8.02	0	16.32	0	5506	0.0	8.02	0.0	16.32	0.0
±10%	5530	+0.4	8.12	+1.2	16.34	+0.1	5489	-0.3	7.99	-0.3	16.3	-0.1
±20%	5550	+0.8	8.17	+1.9	16.36	+0.2	5469	-0.7	7.98	-0.5	16.27	-0.3
±30%	5578	+1.3	8.20	+2.2	16.39	+0.4	5445	-1.1	7.97	-0.6	16.25	-0.4
±40%	5600	1.7	8.24	+2.7	16.41	+0.6	5420	-1.6	7.96	-0.7	16.22	-0.6
±50%	5627	2.2	8.26	+3.0	16.44	+0.7	5390	-2.1	7.96	-0.7	16.15	-1.0

FIGURE 2.14A. Impact of Unbaised Errors on the Response

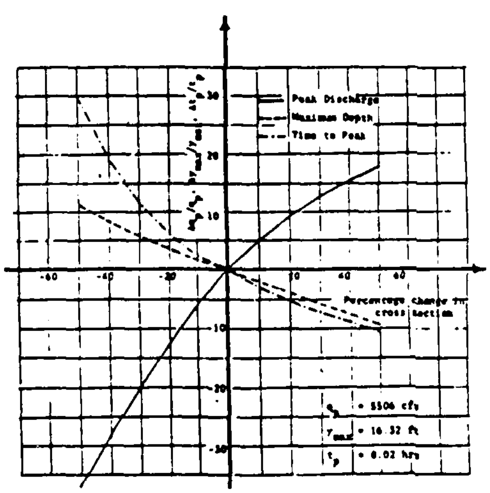


FIGURE 2.14B. Impact of Uniform Errors in the Cross Sections on Response.

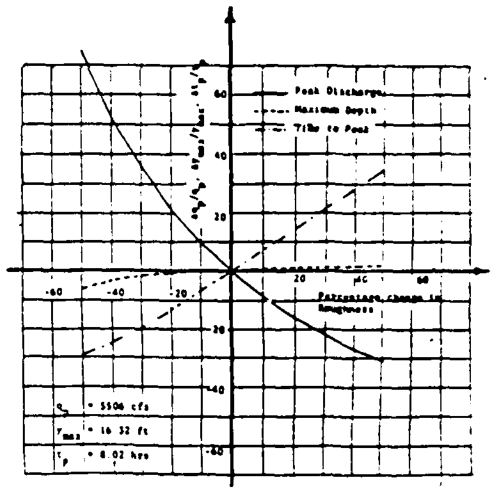


FIGURE 2.14C. Impact of Uniform Errors in the Roughness on Response.

3.0 *DIGITAL IMAGE PROCESSING*

Over the past decade, work by HEC as well as WES, CRREL, and other Corps organizations have utilized satellite remote sensing to support hydrologic investigations. Despite these efforts and activities, application potentials have not been fully realized. Part of the problem, historically, has been with perceived limitations of the 80-meter resolution of the MSS. Perhaps a more important problem has been in the management of Landsat data. Some proponents of Landsat did not fully recognize that land cover was only one of several data sets required for the modeling of a watershed. Even though land cover could be defined in a matter of hours, it still required many weeks to develop the soils, topography and socioeconomic information before the land cover could be "overlaid" on the other data sets. Thus, there has been little incentive to develop expertise in Landsat land cover utilization. The critical missing element needed for success has been an efficient, readily available, method for merging and managing the numerous data sets - what is currently called a "user-friendly" GIS.

Corps research is currently focusing on a range of new satellite sensor capabilities and applications. Landsat Thematic Mapper and SPOT data are being extensively evaluated, and applications are being demonstrated for use in planning, engineering and operational projects and activities. As a result of the recent development of powerful, inexpensive personal computers a host of new image processing and GIS packages now provide many of the original HEC-SAM capabilities on desk-top workstations. These personal computer workstations can operate as "stand-alone" systems that allow the individual to take a 24" x 36" digitizing tablet "off the wall" and quickly develop and manage the data sets required for an mesoscale watershed. At the same time, this personal computer workstation can be networked with remote computing capabilities to become a component in a regional system. This PC capability is in place and can be a major driver in fulfilling through widespread use the benefits of digital format remote sensing and spatial information systems for Corps hydrologic, environmental and operational activities.

Digital image processing in this current study involves review of several related developments discussed in the following sections. First, a review of Computer Environment developments focuses on the introduction of the personal computers built around the Intel 80386 microprocessor which has dramatically altered the 32-bit workstation market.

The second section discusses geometric rectification characteristics of Landsat and SPOT data and requirements for image coregistration and georeferencing for large area mosaics.

The application of statistical pattern-recognition techniques to multispectral remotely sensed data for the purpose of land-cover classification has become commonplace; basic characteristics of land cover classification techniques are reviewed in the third section.

3.1 *Computer Environment*

Introduction of the first personal computers built around the Intel 80386 microprocessor appears to have quickly and dramatically altered the 32-bit workstation market. Previously, this market was dominated by systems built around the Motorola M68000/10/20 chip running the Unix operating system. These systems, geared primarily for graphics and artificial intelligence applications have been priced in the $20,000 and up range.

In the fall of 1986, Compaq introduced the Deskpro 386, becoming the first major manufacturer to bring an 80386 based system to market. Several other manufacturers, most notably Zenith, have also introduced 80386 based systems and IBM is expected to do so sometime this year. In terms of price and hardware performance these systems are quite competitive with their M68000 counterparts. A Compaq Deskpro 386 with 1Mb of RAM and a 130 Mb hard disk can be purchased under the GSA schedule for under $6,000.

In hardware benchmarks, the 80386 chip running at 16 MHz has demonstrated a performance level of 3-4 million instructions per second (MIPS). This compares favorably with many of today's super-mini computers and is considerably faster than an M68020 system.

The 80386 chip is fully compatible with the 8086/8088 of the original IBM PC. The Compaq 386 will run virtually all existing IBM PC applications, a statement not true of the IBM PC/AT. Existing PC applications do not explicitly take advantage of the 386's 32-bit architecture and therefore will not receive the full benefit of the 386's increased speed. They should, however, run at least twice as fast on a 386 as they do on an 8 MHz PC/AT. Most major PC applications packages will be released in 386 versions in the near future.

The biggest shortcoming of the 386 so far is the operating system. Currently available 386 systems run under DOS 3.1 (or Xenix if IBM PC compatibility is not required) which imposes artificial restraints on the hardware. For example, although the 386 can address up to 4 gigabytes of memory, DOS 3.1 retains the 640 Kb limitation from the original IBM PC and PC/AT. Also DOS 3.1 does not support multitasking which is essential to make full use of the hardware capabilities. DOS 5.0 is intended to remedy these shortcomings but it is not clear when it will be available.

The 386 should increase the utility of various IBM PC based image processing systems currently on the market. Among these are ERDAS, Terra-Mar and Decision Images (the ERDAS and Terra-Mar systems are reviewed in Section 4.0). Processing power of the 386 allow these systems to be used effectively for processing large image databases from SPOT and TM. Such a system with an integrated geographic information system can greatly enhance the Corps' capability in image processing and spatial data management by provid-

ing high-powered interactive workstations. Further, these workstations can be interfaced with the Corps' Harris computers to augment current capabilities.

3.2 *Geometric Rectification*

Landsat MSS computer compatible tapes generated prior to 1978 required sophisticated software to produce a geometrically corrected image suitable for use with a geographic information system or for merging with other geometrically rectified imagery. These CCTs, written in band-interleaved-by-pixel pair (now known as X) format, contained no geometric corrections except for the insertion of padding pixels to achieve a uniform line length. Sources of geometric distortion in these data include:

- o *Earth rotation skew*
- o *Variation in scan mirror velocity*
- o *Finite scan time skew*
- o *Aspect ratio due to oversampling*
- o *Earth curvature/panorama*
- o *Altitude and attitude variation*

Earth rotation skew, as its name implies, results from the motion of the earth during the 29 seconds required to scan a single Landsat scene. This distortion is a function of latitude and is greatest at the equator where the maximum displacement is approximately 14 km. This distortion is approximately linear but correction should only be applied between six line boundaries or discontinuities within the image will result.

Scan mirror velocity can be accurately modeled by a sinusoidal error function with a period equal to one scan line and peaks of -7 and +7 pixels at the 25% and 75% points respectively.

Finite scan time skew results from the motion of the spacecraft during the active scan time. This distortion is linear with a maximum displacement of 2-3 pixels across a scene.

The ***MSS data stream is oversampled*** by approximately 40% resulting in a pixel separation of roughly 57 meters within scan line as opposed to the 79-meter spacing between scan lines. Without correction the image would appear to be compressed in the along track direction. This is a linear distortion.

Earth curvature/panoramic distortion results from the fact that the MSS data stream is sampled in equal time intervals rather than equal ground distance intervals. Pixels in the center of a scan line are separated by approximately 57 meters while pixels at either end of the scan line are separated by almost 58 meters. This distortion is roughly proportional to the tangent of the scanning angle as measured from nadir.

These first four sources of geometric distortion are well defined and can be effectively modeled without the use of ground control. ***Altitude and attitude*** (roll, pitch, and yaw) variations present the most difficult problem for geometric correction because of the lack of accurate attitude measurements on which to base a correction. Landsat 1,2, and 3 utilize infrared Earth scanners to determine roll and pitch and a rate-integrating gyro to determine yaw. Uncertainty in these measurements can result in as much as 1 km of positional error in the corrected image.

To produce imagery with high geometric fidelity from these early Landsat CCTs thus requires software that can model the known sources of geometric distortion and utilize ground control information to define the remaining sources of distortion. Typically 20 to 30 control points are required depending on the desired level of accuracy. Locating these points is a timeconsuming process which requires interactive image display capability.

When the EROS Data Center Digital Image Processing System ***(EDIPS)*** system came on-line in 1978 the standard digital product was revised to include geometric correction. The format was also changed to a more manageable band sequential (BSQ) or band interleaved by line (BIL) at the user's option. The EDIPS system utilizes a ground control point library for improved geometric accuracy. The actual geometric quality varies from scene to scene depending on the number and spatial distribution of control points actually used in the correction process. A geometric quality indicator is coded into byte 232 of the header record on the scene attributes file of the CCT. This is a numeric indicator ranging from 0-9 which specifies the number (N + 7)/8, where N is the number of control points used.

Geometric fidelity of MSS and TM data from Landsat 4 and 5 is greatly improved over Landsat 1-3. The processing systems for these data (MIPS for MSS, TIPS for TM) both utilize ground control points for geometric correction, but the biggest improvement is in the satellite itself. In addition to the attitude measurement systems employed on Landsat 1-3, Landsat 4 and 5 have star sensors which improve measurement accuracy by an order of magnitude (Friedmann, 1983). EarthSat's experience shows that these data can be corrected to the Universal Transverse Mercator (UTM) projection with sub-pixel accuracy using only 4 to 6 control points to define a first order coordinate transformation of the form

$$\text{North} = \text{Row}*C1 + \text{Column}*C2 + C3$$
$$\text{East} = \text{Row}*C4 + \text{Column}*C5 + C6$$

An exact solution for C1-C6 can be obtained with only three control points but more commonly additional points are used to obtain a least squares solution, which is less sensitive to measurement errors. The first-order transformation can perform image translation, rotation, independent (row,column) scale change and skew.

Higher order corrections are generally not recommended unless a large number of control points is used because of instability problems in areas with poor control.

The SPOT system also utilizes improved attitude measurement systems, adding a three-axis magnetometer to the system employed by Landsat (Friedmann, 1983). EarthSat's experience with this data shows that its geometric accuracy is as good or better than TM.

3.2.1 *Image Coregistration*

Image coregistration involves the warping of two or more images into a common coordinate system so that they can be combined pixel for pixel. Two common applications of coregistration are multi-date change detection and image sharpening, the use of a high resolution panchromatic image (i.e., SPOT panchromatic) to increase the apparent resolution of a lower resolution multispectral image (i.e., Landsat TM). The accuracy demands of coregistration are usually more severe than in simple georeferencing because the effect of misregistration is more visually apparent. For example, a misregistered multi-date image pair will produce numerous areas of false change, particularly around cultural features, water bodies and field boundaries.

When georeferencing is not required one image can be selected as the master image to which the other image(s) will be matched. In the case of sharpening the master image will obviously be the one with the higher resolution. A set of tie points, high contrast features which can be located and measured on each image, is used to define a least squares solution to a first order coordinate transformation similar to that used for georeferencing. Road intersections, airports and other cultural features make ideal tie points. Water bodies can be used if the water levels are known to be consistent between images. In mountainous areas ridge lines can be used if no other suitable control is available but be aware that different sun angles can introduce errors.

Tie points should be measured using an interactive video display system, preferably one with split screen and interpolative zoom capability. These features can be emulated in software if not available in the display hardware. The split screen feature allows the analyst to view the images simultaneously, insuring that the tie point has a consistent appearance between images and that the same part of the tie point has been measured on each image. Interpolative zoom allows the measurement to sub-pixel accuracy. EarthSat feels that cubic convolution interpolation provides the most accurate enlargement.

EarthSat uses cross-correlation software to further increase tie-point measurement accuracy. This software searches for the maximum cross-correlation in the vicinity of the user-defined tie point. A surface is then fitted to the cross-correlation values in a three-pixel-by-three-line area surrounding the maximum. The tie point is redefined as the location of the maximum value of the

cross-correlation function. EarthSat has found that this technique reduces residual tie point errors by about half a pixel in typical applications.

When georeferencing is also required, EarthSat recommends that only the highest resolution image be georeferenced. The other images can then be matched to the georeferenced image using tie points as described above.

3 2.2 *Georeferencing for Large Area Mosaics*

As indicated above the correction of a single Landsat or SPOT scene to the UTM map projection can be accurately performed without regard for the properties of the map projection itself. However, as the size of the area increases the relationship between image and map projection becomes less linear thus requiring more control points to define a higher order correction or a model of map projection.

EarthSat has developed software that utilizes a two-stage geometric correction using a minimal number of control points. The first stage is a first-order control-point-driven transformation which transforms the image row and column into local UTM northing and easting values. The second step transforms the local UTM coordinates into the desired map projection, possibly another UTM zone, using analytical models to perform the projection transformation.

The map projection transformation algorithms require a substantial amount of computer time and would be prohibitively expensive to execute for each image pixel. To reduce the time required the software sets up a coarse grid (i.e., 16 x 16 pixels) and performs the two-stage transformation process only at grid intersections. Map-coordinate pixels that do not lie on these intersections are evaluated by linear interpolation between the four closest grid intersections.

3.3 *Land Cover Classification*

3.3.1 Supervised vs. Unsupervised Techniques

The application of statistical pattern recognition techniques to Landsat multispectral scanner (MSS) data for the purpose of land cover classification has become commonplace. Both supervised and unsupervised techniques have been employed to achieve fairly accurate Level I categories.[1/]

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1/ Level I categories include urban, agriculture, rangeland, forest, water, non-forested wetland, barren land, tundra, and permanent snow/ice (Anderson, et al., 1976).

The unsupervised approach to classification involves the application of a numerical clustering algorithm which groups image pixels into spectral clusters according to some metric distance, usually the Euclidean distance from the pixel to the cluster mean. These algorithms are usually iterative in that clusters are redefined, merged or split after each pass and classification continues until a stable result is obtained or some predefined number of iterations has occurred. The resulting class map must then be analyzed to assign each class to a cover type. Because of the multiple pass requirement, many unsupervised classifiers can be expensive computationally when applied to large data sets.

The supervised approach requires that the analyst train the algorithm to recognize each cover type to be classified. Training consists of identifying an example of the cover type on the image. The statistical properties of the training sets are used to define decision boundaries which define the classification rule. Commonly used methods to define the decision boundaries include Euclidean distance, Mahalanobis distance and Bayesian maximum likelihood. The last approach, while the most computationally expensive, is generally considered as the most accurate of the three and is the most widely used. The maximum likelihood method seeks to maximize the expression

$$p(i)*p(\bar{x}|i)$$

where p(i) is the probability of occurrence of class i (the *a priori* probability) and $p(\bar{x}|i)$ is the probability of occurrence of observation $\bar{x}$ given class i. Usually the *a priori* probabilities are set to one for each class, since sufficient information is not available to do otherwise. This second term is simply the multivariate normal probability density

$$p(\bar{x}\,|\,i) = \frac{1}{(2\pi)^{n/2}\,|\Sigma_i|^{1/2}}\, e^{\left[-\frac{1}{2}(\bar{x}-\bar{u})^T\,\Sigma_i^{-1}(\bar{x}-\bar{u})\right]}$$

where $\bar{x}$ is the vector of observed (pixel) values, $\bar{u}$ is the mean vector for class i, Σ_i is the covariance matrix for class i, Σ_i^{-1} is the inverse of the covariance matrix, $|\Sigma_i|$ is the determinant of the covariance matrix and n is the number of image bands. In most implementations the natural logarithm of the density function is used to avoid the expense of the exponentiation operator.

3.3.2 Landsat TM vs. MSS

Thematic Mapper (TM) data has several theoretical advantages over MSS in the application of multispectral classification techniques. These are:

- 30 vs 79 meter spatial resolution
- 8 vs 6 bit radiometric resolution
- 7 vs 4 spectral bands

In practice, however, the results of applying conventional classification techniques to TM data have been disappointing. TM has proved to be slightly more accurate than MSS in classifying agriculture, rangeland and natural vegetation and slightly <u>less</u> accurate than MSS in classifying suburban/residential areas. Because of its higher resolution TM is more apt to break the residential category into its individual constituent categories (grass, forest, rooftops, roads). While technically accurate, this tendency is undesirable in most land-cover classifications.

Why does TM not yield significantly higher classification accuracy than MSS? Consider the advantages of TM as stated above. The residential land use classification problem demonstrates that increased spatial resolution can be a mixed blessing using conventional classification techniques. It is unlikely that misclassification of MSS data results from insufficient radiometric resolution. This leaves the additional spectral bands of TM. The 120-meter thermal channel (band 6) has proved to be of little use for classification. The two mid-IR channels (bands 5 and 7) tend to be highly correlated with each other (.95 r^2) and with the visible red channel (> .8 r^2). The visible blue channel (band 1) is highly correlated (.95 r^2) with the visible green and red channels (bands 2 and 3). Thus the spectral dimensionality of TM data is not nearly as great as might be initially expected. This fact can be demonstrated numerically using principal-components analysis. ***Table 3.1*** shows the results of a principal-components transformation of a typical 6-band (thermal omitted) TM. Over 96 percent of the total scene variance can be displayed in only two variables and over 99 percent can be displayed in three variables.

TM data require substantially more computer time to classify than does MSS. A TM scene contains exactly four times the number of pixels in an MSS scene (standard TM digital products use a 28.5-meter pixel compared to a 57-meter pixel for MSS). Assuming that six TM channels are used the classification time would be six times as great using a Euclidean distance classifier or nine times as great using maximum likelihood (time varies with the square of the number of channels for maximum likelihood). When the additional cost of the data is considered it appears that the cost effectiveness of TM for general land-cover classification using conventional techniques may be questionable.

The problem does not lie with the TM data itself. A TM image can convey much more information to a human interpreter than can an equivalent MSS image. However the dominant factor is the spatial resolution of the data; conventional classification techniques cannot take advantage of this factor.

TABLE 3.1: PRINCIPAL COMPONENTS ANALYSIS OF THEMATIC MAPPER DATA

ORIGINAL VARIANCE/CORRELATION MATRIX

BAND	MEAN	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6
1	104.94	173.43	0.94	0.95	0.29	0.74	0.83
2	42.23	0.94	88.65	0.97	0.48	0.80	0.84
3	39.03	0.95	0.97	201.29	0.36	0.82	0.89
4	87.60	0.29	0.48	0.36	890.14	0.61	0.42
5	84.92	0.74	0.80	0.82	0.61	2000.70	0.95
6	32.32	0.83	0.84	0.89	0.42	0.95	553.80

LIST OF EIGENVALUES AND EIGENVECTORS

VECTOR NUMBER	% TOTAL VARIANCE	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6
1	81.3765	0.1790	0.1409	0.2128	0.3624	0.7856	0.3929
2	14.9036	-0.2010	-0.0693	-0.1973	0.8958	-0.1511	-0.3009
3	3.1397	0.5981	0.4099	0.5020	0.1979	-0.4274	-0.0192
4	0.3421	-0.1477	-0.0766	-0.1434	0.1507	-0.4177	0.8687
5	0.1846	-0.7292	0.2554	0.6334	-0.0150	-0.0381	-0.0126
6	0.0535	-0.1275	0.8580	-0.4920	-0.0638	0.0371	0.0016

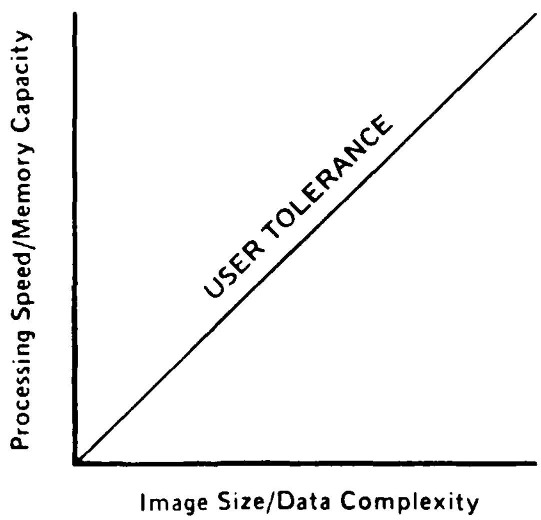
Some studies have indicated that the inclusion of one or more texture channels can increase the classification accuracy of TM data. While this approach has not provided a dramatic increase in accuracy it certainly points the direction toward which research efforts should be moving. The full exploitation of high resolution multispectral data such as TM and SPOT will require significant advances in the areas of machine vision, image understanding and artificial intelligence. A contextual classifier will have to consider not only the spectral signature of a pixel but also the spatial context in which it occurs in order to make the optimum classification.

4.0 *EVALUATION OF PC-BASED IMAGE PROCESSING/GIS SYSTEMS*

Dramatic increases in performance of personal computers over the last ten years has greatly expanded the range of applications to which they can be applied. Many tasks which were in the past restricted to mainframe computers can now be executed quite easily on an off-the-shelf personal computer which can be purchased for under $4000. In terms of processor speed, addressable main memory and amount of on-line disk storage, today's PC rivals the mainframes of the not too distant past. Thus it is now practical to build an image processing and geographic information system around personal computer technology.

Under auspices of the Corps' study, EarthSat evaluated two commercially available PC-based image processing/GIS systems developed by ERDAS Inc.[2/] and Terra-Mar Resource Information Services, Inc.[3/] Benchmark evaluations were conducted in June 1987, at ERDAS's office in Atlanta, Georgia and at Terra-Mar's field office in Columbia, Maryland. Both systems operate on Compaq 386 (or compatible) and IBM PC/AT (or compatible) running under the MS-DOS operating system. In addition, both systems utilize a 512x512x32 bit frame buffer connected to a high resolution RGB monitor to display image, map and graphic data. The evaluations of each system were conducted on an IBM PC/AT running at 8 mHz.

Although the ERDAS/Terra-Mar comparisons were conducted on PC-based computers, both systems are also available on mini and mainframe computers (i.e., SUN, VAX, and PRIME, for example). Functionalities are similar from one computer configuration to another, although speed of operations may vary significantly. In this sense the practicability of image/GIS processsing on a microcomputer (PC) compared to a mini or mainframe computer can be viewed as a three-dimensional trade off:



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2/ Earth Resou[illegible] Data Analysis Systems, Inc. (ERDAS), 430 Tenth Street, N.W., Suite N206, Atlanta, GA 30318, (404) 872-7327), Telex 706327 ERDAS ATL

3/ Terra-Mar Resource Information Services, Inc., 1937 Landings Drive, Mountain View, CA, 94043-0839, (415) Telephone (415) 964-6900, Telex 6503095788 [illegible]

The most suitable hardware configuration thus is dependent on the application, the user, and the user's tolerance in turnaround time.

The comments and comparisons that follow are based on findings in July 1987. It is realized that both ERDAS and Terra-Mar have active and ongoing software development programs and are continuously releasing improvements and changes in their respective systems. Interested readers are encouraged to contact the respective companies for updated information. The comments in this report do not imply an endorsement or recommendation of either system.

Although there are several additional manufacturers marketing PC-based image processing or PC-based GIS systems, the ERDAS and Terra-Mar systems are marketed as integrated turn-key systems. Further, these two systems appear to be the most well known in the domestic market place. ERDAS introduced its first system in late 1980, while Terra-Mar's systems were introduced in early 1984.

Preparatory to conducting the benchmark evaluations, comparison criteria were developed as shown on *Table 4.1*, which provided guidelines to be followed with each system. The results, presented in the following pages, follow an 11-point outline, first describing the ERDAS system, then the Terra-Mar; comparison comments are generally included in the second system description.

TABLE 4.1: IMAGE PROCESSING/GIS SYSTEM **COMPARISON CRITERIA**

Hardware (Sections 4.1.1 and 4.2.1)

1. 80386 based system
2. Co-processors
3. Optical disk

User Interface (Sections 4.1.2 and 4.2.2)

1. Structure
2. Default answers
3. On-line help
4. Batch processing setup

Image, Enhancement Functions (Sections 4.1.3 and 4.2.3)

1. Ability to handle Landsat MSS, TM, and SPOT imagery
2. Ability to handle AVHRR imagery
3. Contrast stretch
4. Spatial filtering
5. Ratioing
6. Principal components linear combinations
7. Intensity, Hue, Saturation

Image Classification Functions (Sections 4.1.4 and 4.2.4)

1. Supervised and unsupervised classifications
2. Training for supervised classification

3. Processing speed benchmark: Bayesian maximum likelihood classification

Georeferencing (Sections 4.1.5 and 4.2.5)

1. Geometric corrections/rubber sheeting
2. Georeferencing of remotely sensed imagery
3. Coregistration of multidate imagery

Polygon Digitizing (Sections 4.1.6 and 4.2.6)

GIS Functions (Sections 4.1.7 and 4.2.7)

1. Overlay
2. Zone generation
3. Attribute handling
4. Report generation
5. Optimal path routing
6. Line of sight computation
7. Post classification filtering to reduce the number of polygons

IP/GIS Interface (Sections 4.1.8, 4.1.10 and 4.2.8)

1. Utilize GIS layers in classification process
2. Create GIS layer from classification

Hard Copy Generation (Sections 4.1.9 and 4.2.9)

1. Ability to produce high quality map output

User Support (Sections 4.1.12 and 4.2.11)

1. Telephone support
2. Software maintainance
3. Frequency and quality of software updates
4. User group
5. Software tool kit for user developed applications

Because descriptive literature, brochures, price schedules, etc., are periodically revised, interested readers are referred to each company for further information or materials.

Following the referenced benchmark evaluations, a brief discussion is included on the recently released PC-ARC/INFO geographic information system developed by Environmental Systems Research Institute.[4]

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4/ ESRI, Environmental Systems Research Institute, 380 New York Street, Redlands, CA 92373 (714) 793-2853

4.1 *ERDAS*

Earth Resources Data Analysis Systems (ERDAS), Inc. is based in Atlanta, Georgia; a satellite office was opened in August 1987, in Rockville, Maryland. The company has been in business over seven years providing consulting services and marketing turn-key systems. Their current system, ERDAS version 7.2 operates on IBM PC compatibles including the Compaq 386 and several minicomputer systems including VAX, PRIME, Data General and Gould/SEL. ERDAS has sold approximately 435 systems, 75 percent of which are PC-based. Within the Corps', there are currently 18 ERDAS installations, of which 10 are PC-based. ERDAS PC systems can operate as intelligent work stations to ERDAS minicomputer systems, as well as ARC-INFO minicomputer systems, via a high speed IEEE-488 interface.

The ERDAS system is packaged into nine separately priced software/hardware modules - Image Processing, Geographic Information System, Tape input/output, Color Hard Copy, Polygon Digitizing, Video digitizing, high resolution color scanning, Topographic Data Processing (including Digital Elevation Modeling), and a new vector graphics module called the Enhanced Graphics Package (EGP). The base system includes a core module and either the Image Processing or GIS module. ERDAS can provide a complete turn-key system or the necessary hardware/software components to convert an existing PC. ERDAS is also a distributor of PC-ARC/INFO which is a vector based GIS produced by ESRI and tied to a relational data base, PC INFO, written by HENCO.

4.1.1 *Hardware*

ERDAS runs on an IBM PC/AT compatible or a Compaq 386 with a minimum of 512 kB of RAM and an 80287 or 80387 math co-processor. A minimum of 30 mB of disk storage is required but since a fully configured system requires almost 20 mB to store software and system files most users will require more. ERDAS can configure a system with internal hard disks ranging from 30 mb to 260 mb. A 512x512x32 bit frame buffer, an RGB monitor and a joystick or mouse complete the standard hardware configuration. The frame buffer can display 8 bit images in red, green and blue along with eight independent one-bit overlays and a cursor. The frame buffer supports hardware pixel repeat zoom (2-16x), roam and fast histogram acquisition. When the system also includes PC ARC/INFO, another 30 mb disk drive, an additional 128 K of RAM, and an EGA or CGA monitor is required.

Optional hardware includes a 9-track tape drive, coordinate digitizer, color ink-jet printer, video digitizer, color film recorder and an 800 mb optical disk and a 4K x 4K color scanner. An 8 pen plotter can be included with PC ARC/INFO.

4.1.2 *User Interface*

The ERDAS system is menu driven with a multiple level menu structure. The main menu contains an entry point for each ERDAS module as well as a user defined menu. Menus are defined in editable ASCII files so the user can easily redefine the menu structure. The menu can be bypassed by experienced users by simply entering a program name rather than a menu item number. Online help is available to provide information about any menu item as well as several general topics. At the menu level the system maintains a command cache with the ten most recent commands entered. The user can scroll through these with the up/down arrow keys and edit them with the right/left arrow, insert, delete and backspace keys.

The system can be operated in batch (unattended) mode as well as interactive mode. The preparation of batch command files is facilitated by AUDIT mode and PREP mode. AUDIT mode automatically creates a batch command file during processing so that the same steps can be repeated later or the file can be printed for a hard copy file copy or a quality assurance audit. PREP mode is similar to AUDIT mode except that no processing is performed. While in PREP mode the file system automatically generates an end-of-file condition for any disk read request so that no processing can be performed. Users must be conscious of this when developing their own applications so that all user interaction occurs before the first diskread attempt. Audit files generated by PREP and AUDIT modes can be modified with any ASCII text editor. ERDAS programs may be interrupted allowing the user to use non-ERDAS programs without having to wait for the original program to be completed.

Within each program the user responds to a series of prompts to specify the action to be taken. Most prompts provide context-sensitive default values which can be taken by entering a carriage return. If the user wishes to take all the default responses he may enter <CTRL>D to do so automatically. After the user enters <CTRL>D the program will pause if a prompt is encountered that has no default response.

Before terminating a response with a carriage return the user can edit it with the right/left arrow, insert, delete, and backspace keys.

File system help can be obtained for any prompt requesting a disk file name by entering a valid MS-DOS wild card specification. This will result in the appearance of a directory listing of all files matching the wild card specification. The user can then select the desired file by using the up/down arrow keys to scroll through the directory.

Any valid FORTRAN arithmetic expression can be entered in response to any prompt which expects a numeric response.

4.1.3 *Image Enhancement Functions*

ERDAS can manipulate any 4, 8, or 16 bit digital images. This includes Landsat MSS and TM, SPOT, AVHRR, aerial scanner data and scanned black-and-white or color aerial photography. In order to enter data into the system the user must have a tape drive or have his tape converted to floppy disks. ERDAS tape input programs can handle a variety of formats specific with the exception of the X-format (band interleaved by pixel pair) and AVHRR programs. The generic input programs for BIL, BSQ and BIP can accommodate Landsat MSS/TM and SPOT formats. Image file size is not limited by the 32 MB MS-DOS maximum disk partition size, only by the physical limitation of the storage device.

A 512x512 section of an image can be displayed on the color monitor. The display program will perform an automatic linear stretch of the image if desired. ERDAS automatically created a decimated version of each image file greater than the 512x512 pixel area. This allows the full image to be viewed on the display screen for selection of full resolution windows. The image can also be displayed with pixel repeat zoom. ERDAS requires less than 15 seconds to display three bands from a six-band image.

Image-enhancement capabilities consist of contrast enhancement, filtering and multi-band combinations. All operations can be performed disk to disk so that the processing area is not limited to the screen size.

Contrast enhancement techniques include "histogram equalization" and an interactive intensity function manipulation program. Histogram equalization appears in quotes because this ERDAS function actually performs a histogram dependent linear stretch. The histogram used can be acquired from the entire screen or any rectangular subset. Histogram acquisition is accomplished quickly through the frame buffer hardware. Interactive intensity function manipulation allows the user to interactively modify the intensity transformation functions for the red, green and blue channels independently or simultaneously. The resulting functions are graphed on the display screen. While this capability is powerful it can be difficult to use and its usefulness is substantially diminished by the lack of a histogram display. Presently this display is only available when printing out the file statistics.

Image filtering operations include convolution with up to a 16x16 kernel and the creation of a texture image which displays the localized image variance.

Multiple band operations include band ratioing, linear band combinations and principal components analysis. Band ratios can be scaled by a user specified multiplicative factor. Principal components images can either be scaled by specifying a multiplier or they can be automatically scaled according to the variance (eigen value) of the transformed image. Statistics for principal components analysis can be acquired from any rectangular subset of the image. However the system will not allow area selection from a

displayed image, the coordinates must be entered through the keyboard, but ERDAS does a separate program called CURBOX to acquire on screen coordinates.

A new program, IPX, performs fast arithmetic operations on images stored in the frame buffer. Operations which can be performed include:

o	x = f(x)	Single band intensity transform
o	x = f(x) op g(y)	2 band transform and combination
o	Convolution	
o	Warping	

f(x) and g(y) can be any valid FORTRAN function but they are restricted to the range 0-255. "op" can be an arithmetic (+,-,*,/) or a logical (AND, OR, XOR) operator. The convolution operation is restricted to integer kernel coefficients. A standard library of filters is provided and the user can add new filters or create new libraries as desired. The warping operation performs a first order coordinate transformation using nearest neighbor resampling.

4.1.4 *Image Classification Functions*

ERDAS provides a powerful complement of software to perform multispectral classification. The supervised classification program MAXCLS provides Euclidean distance, Mahalanobis distance, and maximum likelihood classification methods and allows the use of a priori probabilities. MAXCLS can also generate an optional probability file which can be used to mask out pixels which have been classified with low confidence levels. A chi-square table provides threshold values for various confidence levels.

The ERDAS MAXCLS module is capable of classifying a 512x512 7 band image into nine spectral classes in 191 minutes on an IBM PC/AT running at 8 mHz. ERDAS can perform MAXCLS on the entire image file on the disk. Given a large enough disk this means training samples from several subimages can classify a full Landsat TM or SPOT scene.

Training sets for supervised classification can be defined either interactively on the display screen using the mouse or joystick or the scene can be digitized as polygons on a map with the coordinate digitizer. The second option requires a georeferenced image. After selecting each training area the user may elect to view a parallelepiped alarm on the display screen. This highlights the pixels which fall within the class parallelepiped as defined by the training set minimum and maximum band values. The alarm is performed on the displayed screen bands.

Another useful feature is the ability to extract training statistics from an image using polygons which were drawn on a different sub-images or temporal image sets. Thus, a principal com-

ponents or ratio image could be used to delineate training areas which could then be applied to the raw bands for extraction of multivariate training statistics. The different images must share a common coordinate system.

Training set evaluation programs include ELLIPSE which plots the equal probability ellipsoids on two-band scatter plots, SIGDIST which computes a matrix of the Euclidean distances between class means and CMATRIX which performs an actual classification on the training set pixels and reports the result in matrix form. Utility programs are provided which can combine signature files, delete signatures from a file and combine two or more class signatures into a single class.

One inconvenient feature of the system is that in order to classify only a subset of spectral bands a copy of the image must be created containing only the bands to be classified. This can be time consuming and wasteful of disk storage.

Two unsupervised classification procedures are provided by ERDAS. The module CLUSTR implements a two pass sequential clustering algorithm which groups pixels according to Euclidean distance from the class mean. Clusters are automatically merged or split based on user specified minimum cluster separation and maximum cluster radius. The first pass acquires the cluster statistics and the second pass performs a minimum distance classification. CLUSTR can partition an image into as many as 255 distinct spectral classes.

The module STATCL can partition an image into as many as 49 spectral classes. Classes are selected by moving a 3x3 window through the images in search of areas which are spectrally homogeneous and separable from other classes. STATCL does not classify the image but creates a signature file which can be used by the supervised classifier MAXCLS.

The module CLASOVR permits the simultaneous viewing of a image and its associated class map. Two bands of the image can be displayed in two color guns (red, green or blue) while the class map is displayed in the third. Using a mouse or joystick, various highlighting and toggling options are provided to isolate a single class or range of classes. This option is particularly valuable in assessing the results of an unsupervised classification.

4.1.5 *Georeferencing*

ERDAS supports control point driven geometric correction using a first order (affine) coordinate transformation. They will release a new rectification program using the n^{th} order coordinate transformation. This will allow a user to select the degree of accuracy or fit needed for a particular project. Nearest neighbor, bilinear and cubic convolution interpolation options are provided.

Resampling of images requiring significant rotation is accelerated by segmenting the image into tiles. This greatly reduces the input/output time required to perform a rotation.

A ground control point editing program is provided which helps to automate the control point selection process. This program accepts map coordinates from the coordinate digitizer or keyboard and image coordinates from the mouse/joystick or keyboard. No interpolative zoom option is available so image coordinates can only be measured to the nearest whole pixel. ERDAS supports twenty (20) different map projections so that almost any map can be accurately digitized.

Multiple image mosaicking is facilitated by the program STITCH which automatically combines images which have been referenced to a common coordinate system. Mosaicking is performed using a straight splice seam where the last image specified dominates in overlap areas. There is not a straightforward method for radiometric matching.

4.1.6 *Polygon Digitizing*

ERDAS supports digitizing in point, vector and polygon modes. Special software is provided to allow digitizing polygons across multiple map sheets. Polygon digitizing is perhaps the weakest part of the ERDAS system. Polygons must be digitized as polygons so that common boundaries are digitized twice. Inconsistent digitizing of common boundaries is a persistent problem. It can only be solved by over digitizing the first polygon so that it infringes into the domain of its neighbor. The common boundary is then digitized exactly for the neighbor. Since the polygons are rasterized in the same order as they were digitized the result is an accurate common boundary with no intervening gaps. For the same reason, island polygons must be digitized last or they will be overwritten when their surrounding polygons are rasterized. Digitizing a complex map of polygons can only be accomplished with a tremendous amount of preliminary planning. ERDAS does offer PC ARC/INFO which has an excellent digitizing package, so the user has an option of digitizing data for the ERDAS system.

4.1.7 *GIS Functions*

ERDAS provides a raster based geographic information system. GIS files are stored as a matrix of 4, 8 or 16 bit grid cells each containing a class number. Class numbers are linked to a list of class names and a color palette. Wraparound, a process of duplicating colors assigned to lower number classes occurs for 16 bit GIS files with values over 255. Attribute data can be linked to the GIS file by using the summary program, but must be run more than once for multiple file relationships.

The GIS module of ERDAS contains programs that include the classical concepts associated with GIS operations. A summary of the GIS programs appears below:

RECODE - this option permits the reassignment of class numbers of any or all classes within a GIS file.

OVERLAY - this option combines up to four GIS layers with either the maximum or minimum class value dominating. Each layer can be recoded (assigned new class values) prior to the overlay process.

INDEX - this option combines up to four GIS layers using a weighted sum algorithm and optional recoding of each layer.

MATRIX - this option combines two layers by assigning a unique number to each possible combination of class values. Each layer can be recoded prior to combination.

SEARCH - this option performs proximity analysis on a GIS layer. It can be used to generate buffer zones around classes of interest such as streams, roads, etc..

CLUMP - this option performs contiguity analysis on a GIS layer. It locates clumps of contiguous cells according to a user specified connectivity radius and assigns a unique identifier to the contiguous cell polygon.

SIEVE - this option screens out clumps which do not meet a user specified size criteria.

AGGIE - this option aggregates a GIS layer to a coarser grid cell. The new grid cell must be an integer multiple of input cells. The dominant value is assigned to the output cell unless an optional priority class occurs in the cell. This allows point and linear features to be maintained during the aggregation process.

SCAN - this option performs filtering on a GIS layer. The size and shape of the filter domain are user specified. The filter techniques include sum of class values, average class value, maximum value, minimum value, median value, majority value, minority value, total number of values, density, diversity, and boundary detection.

SUMMARY - this option performs a cross tabulation report of two GIS layers listing class names and area statistics.

GISEDIT - this option permits interactive editing of a GIS file displayed on the color monitor. The editing process involves local recoding of GIS cells. The area to be recoded can be delineated by points, vectors or polygons drawn on the display screen via the joystick.

Linking the different GIS programs can produce sophisticated statistical and Boolean map modeling as well as producing tabular and graphic results associated with relational vector GIS programs. Unfortunately, the procedures may not be as easy as a vector approach. With interface to ARC/INFO the raster files can be transferred to PC ARC/INFO and the user can have access to the capabilities associated with a vector GIS that has a topological structure and a relational data base schema.

4.1.8 *IP/GIS Interface*

Output from all ERDAS multispectral classification modules is automatically generated in GIS file format so that it can be processed by any GIS module and combined with other GIS layers. Image and GIS data can be combined using the module MULT which performs a multiplication of an image and a GIS layer. MULT can be used to mask image area outside a region of interest.

GIS layers can actually be used as image bands in the classification process although the procedure for doing so is not straightforward. By changing the filename suffix of the GIS layer from ".GIS" which designates a GIS file to ".LAN" which designates an image file, the GIS layer can be treated as an image and copied into a file already containing a multiband image. The interface allows for statistical programs in image processing to be used with the GIS files. This capability allows for statistical modeling not generally associated with a vector GIS.

4.1.9 *Hard Copy Generation*

ERDAS supports color hard copy generation through a color ink jet dot matrix printer. This device is rather slow and multiple panels are required to print large areas. Both image and GIS files can be printed in this manner.

Film products can be produced through an optional film recorder which can produce copies of a 4096x4096 array on 35mm, 4x5 or 8x10 film.

ERDAS does not support a pen plotter interface, but with the ARC/INFO interface the user can convert raster files into vector files and use PC ARC/INFO with an 8 pen plotter.

4.1.10 **The ERDAS-ARC/INFO Link**

The ERDAS-ARC/INFO link, shown in ***Figure 4.1***, provides a process to convert ERDAS GIS files into ARC coverages (raster to vector) and to convert ARC coverages into ERDAS GIS files (vector to raster). The conversion and exchange capabilities will allow analysis (such as attribute modeling using a relational data base, polygon overlay, and clipping) of raster ERDAS files in ARC vector

format. ARC's sophisticated digitizing capabilities can be used to capture data in ARC vector files and then converted to ERDAS raster GIS files. (Also, the ability to display ARC coverages over ERDAS digital imagery will allow timely updating of cartographic databases through change detection.)

At this writing, raster-to-vector and vector-to-raster conversion routines are available. In current development is an enhancement to allow user access to both ERDAS and ARC/INFO commands via Techtronic terminal emulation. The result will enable vector mapping with related attributes overlaid on color imagery.

The PC ARC/INFO software consists of seven modules. The software packages have the following capabilities listed below:

- Cartographic data base generation and management.
- Digitizing, editing and updating of cartographic data; conversion of data from other formats; and capability of reading and integrating scanner data into a data base.
- Tabular data base generation and management - tabular data entry and update, file management, statistical analysis, and tabular report generation.
- Cartographic analysis - interpretive mapping, digital terrain analysis, polygon overlay, point-in-polygon calculations, buffer, and other types of map analyses.

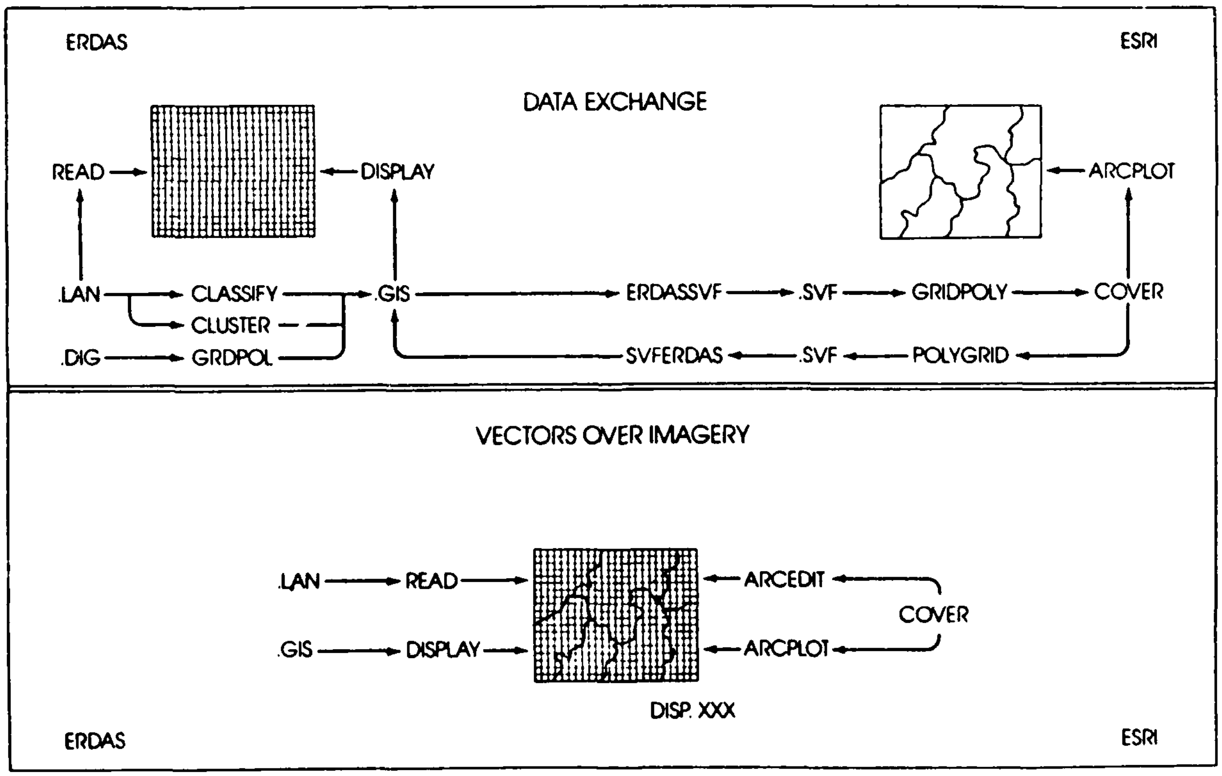

FIGURE 4.1. ERDAS ARC/INFO INTERFACE

- Cartographic display - polygon, line, and point mapping, labeling and map annotation, in hard copy as well as interactive display.

- Query capabilities - searches of given areas for cartographic or tabular data related to those areas; searches for areas with given set of characteristics.

- ERDAS interface allowing raster data to be converted into ARC files and the vector data transformed into ERDAS raster files.

The PC ARC/INFO software can provide a user with a range of geoprocessing capabilities. These can be grouped into three basic categories:

- Map automation - programs for the entry of x, y coordinates and related attribute information of map elements (points, lines, and polygons).

- Data manipulation, analysis, and management - programs for interactive modeling, distance search, map overlay, optimum corridor location, statistical analysis, and other functions.

- Output and display - programs for making displays on graphic terminals, printer maps, and pen plots in black-and-white or color, and other products. Tabular date can be listed in a variety of report formats.

The PC ARC/INFO system offers the technological means of managing multiple and wide ranging types of spatial and statistical data. The GIS and Data Base Management System (DBMS) components of PC ARC/INFO's integrated series of products provide map digitizing, data transfer, relational data base management, map overlay, display, query, interactive graphics editing, address geocoding, and network analysis. The programs are flexible. The software provides device independent drivers to permit users to select from a variety of standard display monitors, digitizers, and plotters.

PC ARC/INFO can organize, store and provide a research base for geographic data. It can compare, integrate, and combine different data sets, e.g., census data, land use data, highway/network information, property value data and natural resources attributes. The programs offer the user the ability to perform various types of cartographic analysis and display, such as land suitability/-capability studies demographic trends, flow analysis and related inter-locational analyses.

4.1.11 *Future Products*

ERDAS has recently released a vector graphics module for its PC based system only. This module will allow a relational data base of graphics symbols, text and attributes to be linked to a GIS file or image and displayed on the color monitor. Graphics symbols and line styles can be designed by the user and can be displayed at any scale and rotation angle. Text fonts, color, scale and rotation angle are also user selectable.

Although this module is powerful and permits high quality graphics annotation, it involves a complicated and cumbersome process to create the required support databases, but according to ERDAS the process is being simplified in the next release.

The next release of ERDAS will contain a disk roam function which will permit scrolling through an entire image, regardless of size, under mouse control. Pull down menues and 3-D image display are other significant features being developed.

4.1.12 *User Support*

ERDAS provides a 90-day warranty period during which time telephone support is available. After the 90-day period telephone support is only available on a yearly subscription basis which also provides all software updates, new documentation, and new releases. Nonsubscribers, however, may submit queries and bug reports to ERDAS in writing. ERDAS warrants its product in writing for any logic errors in the software. ERDAS also supports and coordinates an ERDAS User Group which holds annual meetings to discuss and exchange technical problems, ideas, and applications. A newsletter is published by ERDAS for information exchange between ERDAS and users.

Custom applications which adhere to the ERDAS user interface can be created using routines and procedures available in the ERDAS tool kit. The tool kit, written in FORTRAN 77, includes libraries and macros for compiling and linking user-developed code with the system. The tool kit includes a Programmer Reference Manual.

4.2 *Terra-Mar*

Terra-Mar Resource Information Services, Inc. is based in Mountain View, California with field offices in Houston, Texas, Denver, Colorado and Columbia, Maryland. The company has been in existence for over eleven years, and for three years has marketed PC based image processing and, more recently, a separate geographic information system. Their current system operates on IBM PC/AT, SPERRY PC/IT, and Compaq 386 and compatible hardware. Terra-Mar also markets specialized software packages for geophysiscal data processing as well as a variety of value-added services. Terra-Mar has provided over 100 PC-based installations with one or more image processing GIS, or geophysical software modules. To date, most of Terra-Mar's installations are in various private sector organizations, principally extractive resource industries.

The Terra-Mar system consists of an image processing module, MicroImage, and a vector based geographic information system, Terra-Pak. A third module, T-mapper, is a multifunction contour mapper not included in the present evaluation. A Digital Elevation Modeling capability will soon be released. Each is separately priced and can be run as a separate independent system. Terra-Mar provides turn-key systems or upgrade kits to convert a customer's PC into an image processing/geographic information system.

4.2.1 *Hardware*

MicroImage runs on an IBM PC/AT compatible or a Compaq (or other) 386 with a minimum of 512 kB of RAM and an 80287 coprocessor. Terra-Pak requires a 32 bit (M68000) coprocessor card with 4 mB of RAM. This coprocessor card plugs into the backplane of the PC and uses MS-DOS to provide file handling functions. The combined IP/GIS system requires about 10 mB of disk storage for program files. A 512x512x32 bit frame buffer permits the display of 8 bit images in red, green and blue along with 8 independent one-bit overlays and a cursor. A mouse is used for user control of the cursor. The frame buffer supports hardware pixel repeat zoom (2-16x) and roam and fast histogram acquisition. A 14 or 19 inch high resolution RGB monitor is used for image and graphics display.

Optional hardware includes a 9-track tape drive, coordinate digitizer, color ink-jet printer, video digitizer, color film recorder, optical disk and pen plotter.

4.2.2 *User Interface*

The Terra-Mar system is also a menu driven system. The tree structure of the menu does not have the same logical groups as he ERDAS system. Many dissimilar functions are grouped into one large menu, and no online help is provided.

The system can be operated from a standard MS-DOS batch command file but no automated facility is provided for creating such a file. This can be accomplished using any ASCII text editor and knowledge of the proper command sequence.

Within each program the user responds to a series of prompts to specify the action to be taken. Default values are seldom provided. Command line editing can be performed prior to pressing the carriage return by using the right/left arrow, insert, delete and backspace keys.

File system help can be obtained by entering the file qualifier desired. All files with names ending in this qualifier are then listed at the terminal. The user can select the desired file by using the up/down arrow keys to scroll through the list.

4.2.3 *Image Enhancement Functions*

Terra-Mar can read Landsat MSS and TM, SPOT and AVHRR data tapes. All image data is stored and processed in 8 bit format. Image size is not limited by the 32 mB DOS partition size, rather only by the physical limitation of the storage device. Terra-Mar can store and access a full TM scene given sufficient disk space.

A 512x398 section of an image can be displayed on the color monitor. The rightmost 114 columns are reserved for various purposes such as histogram display, intensity table display, etc. The display program can perform a variety of contrast stretches including linear, true histogram equalization, exponential and logarithmic stretches. Bands can also be created as ratios; the band ratioing capability resides within the image display module. Ratios can be scaled via a multiplicative factor and the system will suggest an appropriate factor. Images can be displayed at full resolution, decimated, or with pixel repeat zoom. Terra-Mar automatically creates a decimated version of each full scene image. This allows the full scene to be viewed on the screen for the selection of full resolution windows. Image display on the Terra-Mar system is significantly faster than on the ERDAS system.

All Terra-Mar image processing functions process only the image area currently displayed on the display screen. No disk-to-disk processing is performed. Thus the system is incapable of full scene image enhancement or classification. This is a major limitation which, according to Terra-Mar, will be addressed in a future software release.

In addition to the contrast enhancement options built into the display routine, Terra-Mar provides an interactive intensity function manipulation program which is similar to the one provided by ERDAS. The Terra-Mar version is more useful in that the histograms of the bands are displayed along with the intensity transformation function. Terra-Mar's contrast enhancement module does not allow the use of a subimage area for histogram acquisition; histograms are always taken from the full display window.

Single band images can be pseudo-colored using a dynamic density slicing program. This provides a flexible mouse interface to control the gray scale range and color. The resulting color bar annotated with gray values is displayed in the right hand portion of the screen.

While the ERDAS system presently allows up to a 16x16 kernal, the Terra-Mar system's image filtering is limited to convolution by a 3x3 kernal (to be upgraded in their next release). The filter coefficients must be integer values and there is no provision for post-filtering scaling.

Multiband operations include band ratioing (in the display program), principal components analysis, RGB (red, green, blue) to IHS (intensity, hue, saturation) and IHS to RGB transformations. No general linear combination (user defined weights) is provided. Statistics for principal components analysis can be acquired from any rectangular subset of the image.

RGB to IHS and IHS to RGB transformations are excellent tools for image enhancement. For example, an image can be transformed into IHS space, its saturation can be increased and the result can then be transformed back into RGB space for display on the color monitor. These modules can also be used to sharpen a multispectral image with a higher resolution panchromatic image by transforming the multispectral image to IHS substituting the panchromatic image for the intensity and transforming back to RGB.

4.2.4 *Image Classification Functions*

Terra-Mar provides supervised and unsupervised parallelepiped, unsupervised Euclidean distance, and supervised maximum likelihood classifiers. A priori probabilities cannot be used with the maximum likelihood classifier and no probability file is generated. Instead the user must specify a minimum probability level for each class. Pixels falling below the minimum level for all classes are designated as unclassified.

Terra-Mar's maximum likelihood classifier requires 187 minutes to classify a 512x512 7 band image into 9 classes on an IBM PC/AT compatible computer running at 8 mHz.

Training sets for supervised classification are defined interactively by screen digitizing polygons. The color for each class is determined when the training area is defined and there does not seem to be a mechanism for changing the color assignments.

The unsupervised Euclidean distance program allows the user to specify initial seed values for clusters. This is a useful option which enhances the effectiveness of the clustering process.

As in the ERDAS system, training sets can be viewed along with two band scatter diagrams to get a visual feel for class separability. Terra-Mar, however, provides no quantitative separability measures such as the contingency matrix or distance between class means.

Terra-Mar provides an interactive pixel slicing classifier which is, in essence, a three band color density slice program. The mouse is used to interactively highlight gray scale ranges in each of the three colors. Up to eight classes (red, green, blue, yellow, magenta, cyan, black, white) can be designated through the interaction of the colors.

Class maps can be viewed along with a color image through the used of the FADE module. FADE allows a three color image can be displayed along with the class map. Terra-Mar displays the class map in the overlay channel rather than using one of the three primary color channels. FADE uses a mouse interface to interactively select the class(es) to be highlighted and to fade the color intensity so that the background image shows through the graphics overlay.

4.2.5 *Georeferencing*

Terra-Mar supports control point driven geometric correction using a 1-5 order coordinate transformation. Nearest neighbor and cubic convolution interpolation are provided. A control point program, called (GEOCODE), is provided which allows the interactive selection of image-image or image-map control points. Map control points are selected using a coordinate digitizer. As with the ERDAS system, no interpolative zoom option is provided for more accurate screen digitizing of control points.

Terra-Mar does not provide an image mosaic program as is available on the ERDAS system.

4.2.6 *Polygon Digitizing*

The Terra-Pak module supports coordinate digitizing of points, vectors and polygons. Polygons are digitized by individual arcs which cross at node intersections. The arcs are automatically clipped at each node and assembled into polygons by Terra-Pak. The user is not required to digitize individual nodes or to enter left and right hand polygon designators. Each polygon is given a unique identifier by the system so that the user can assign attributes to it. Island polygons are automatically handled without the necessity for pipestem links.

The Terra-Mar digitizing interface is superior to that provided by ERDAS and appears comparable to the ARC/INFO digitizing interface.

4.2.7 *GIS Functions*

Terra-Pak is a vector based GIS developed by Forest Data Consultants which utilizes a proprietary relational database to store and manipulate attribute data. All spatial data layers and attribute data are stored in a single database. Terra-Pak maintains a log of all database transactions which can be reviewed at any time.

Up to 10 attributes can be associated with any map feature. Attributes can be integer or floating point numbers, character strings, dates, vectors or 2-D or 3-D matrices. Vectors and matrices count as a single attribute towards the limit of 10. Attributes are automatically transferred into any derivative maps created by Terra-Pak.

GIS analysis functions consist of filtering, zone generation and overlay. These functions are specified through the use of an English-like query language. Individual steps are required for query compilation, data extraction, filtering, zone generation, overlay and map generation. This process is currently very cumbersome but, according to Terra-Mar, will be streamlined in a future release.

The filtering process allows the deletion of map features by specifying Boolean conditions for attribute data. The Boolean condition can be quite complex allowing for sophisticated filtering function to be applied in a single pass through the map layer.

Zones can be generated around any point line or polygon. In the case of polygons, zones can be generated inside or outside of the boundary. Different zone widths can be employed for different features in a single pass.

Any number of map layers can be overlaid in a single pass. Boolean and arithmetic operators are used to control the overlay process.

Map output is generated on a pen plotter or displayed on the color monitor. Color and shading is user specified and a legend can be created automatically. Map scale is also user selectable.

Terra-Pak can produce tabular summary reports including acreage and attribute data. Reports can be sorted and can include subtotals.

4.2.8 *IP/GIS Interface*

Its major limitations are its user interface and its inability to handle map projections other than UTM. While ERDAS has interfaced its image processing, raster GIS and ARC/INFO's vector GIS, Terra-Mar has not yet implemented an interface between the MicroImage and Terra-Pak modules. This, however, is presently being developed for future release.

4.2.9 *Hard Copy Generation*

Terra-Mar supports hard copy paper output through a color ink jet printer similar to that supported by ERDAS. Film products can be produced through an optional film recorder which can produce copies of a 4096x4096 array on 35mm, 4x5 or 8x10 film.

Terra-Pak uses a multi-pen plotter to produce high vector quality map output.

4.2.10 *Future Products*

Terra-Mar is currently working on a new release of Micro-Image which will allow full scene image processing, digital terrain data processing and an interface to the Terra-Pak system. A future release of Terra-Pak will contain a revamped user interface and an interface to MicroImage.

4.2.11 *User Support*

Terra-Mar provides a one-year warranty period during which time software updates and telephone support are provided free of charge. After the one-year period this service is available on a subscription basis. Software revisions and updates are distributed twice yearly.

Also available as a purchase option is a Terra-Mar image processing software tool kit package with documentation. Sub-routine code, written in FORTRAN and assembler code, is provided to users to integrate their own programs into the Terra-Mar system.

5.0 *ROLE OF REMOTE SENSING AND INFORMATION SYSTEMS IN SPECIFIC TASKS*

This section addresses the role of remote sensing and information systems as they relate to specific tasks associated with hydrologic and flood-damage analyses. The discussion begins with the conviction that the Corps of Engineers must have ready access to PC-based, desk-top workstations with strong GIS capabilities and, ideally, inclusion in a local, district, or national level-network illustrated by Figure 1.1. Key points developed in the discussion are summarized in *Table 5.1*.

5.1 *Develop Flood Frequency Series Through Statistical Analyses of Stream Gauging Records*

A frequent requirement in hydrology is the development of estimates of the 2-, 5-, 10-, 20-, 25-, 50-year, etc., floods for a point along a river. If good streamflow records are available, analysis of historic floods is an attractive approach. If the length of the gauge record is sufficient and the gauge is located at the point of interest, the only role of remote sensing would be to determine whether there have been significant shifts in watershed land use or in the stream during the period of record. Historical photography and satellite imagery of the last decade is generally available for this purpose.

As a quantitative indicator of significant land use change during a period of record, the historical imagery could be used to estimate coefficients such as the SCS curve number. Even though the adequacy of the curve number can be questioned, a major change during the period of record could indicate a need to adjust the flows while relative constancy in the curve number could justify use of the record "as is" even though there may have been some development.

The key to this argument is that a watershed can experience some levels of land use change without producing a measurable impact on the flood frequency curve, especially the lower return periods such as the 20-, 25-, 50- and 100-year events. Some watersheds near major urbanizing centers may have stream flow records extending back 40 or 50 years which should give a sound flood frequency series. However, these watersheds can be undergoing "step-function" land use changes over a period of two or three years. Although imperfect, hydrologic models using land use based input parameters defined by remote sensing techniques can be used to investigate the seriousness of the land use changes on the reliability of the "total period" flood frequency curve.

More often, the stream gauge is not at the point of interest and sometimes not one gauge has an adequate record anywhere in the watershed. In these watersheds, one or more gauges in the region must be analyzed and the results transposed to the point of interest. In such cases, remote sensing and GIS can be very important tools. Remote sensing can be used to define the land-

TABLE 5.1: THE ROLE OF REMOTE SENSING AND INFORMATION SYSTEMS IN SPECIFIC HYDROGRAPHIC TASKS

OBJECTIVE	APPROACH	ISSUES/INFORMATION REQUIREMENTS	ROLE OF INFORMATION SYSTEMS & REMOTE SENSING
1. Develop <u>Flood-Frequency Series</u> through Statistical Analysis of Stream-Gauging Records	Analyze Streamflow records of watershed of interest or others in region using statistical approach such as Log Pearson Type III	o Lengths of records o Quality of records o Management of Data o Shifts caused by watershed changes	o Remote Sensing . Detect significant watershed changes during period of record early watershed - aerial photography (digitize and register broad categories: manage with GIS) . Recent - MSS for areas 100 square miles o Information Systems . GIS - use to manage any change detection - determine watershed areas and conditions - assess similarity among watersheds when several gauges are used . Archived Data - USGS-WATSTORE, EPA-Reachfiles, USDA-Water Data Laboratory . DCP's for data consistency by recording on one time base
2. Use mathematical models to estimate <u>runoff from real or simulated, single event storms</u> for: o Hydrologic studies requiring a hydrograph or peak flow o Synthetic Flood frequency series	Real or simulated rainfall (or snow melt) and current/anticipated watershed conditions input to: HEC1 - generate watershed hydrograph DWOPER - option for channel routing STORM - option for hydrograph synthesis on urban watershed	o If using real rainfall-translation of point measurements to spatial distributions o HEC1 - watershed area . SCS - curve number option for Loss Rates - Land Cover & Soils . Snyder Option - lengths of channels, location of centroid, coefficients . Clark Option - distribution/connections of slopes and roughnesses for time-area curve	o If user runs HEC-1 with no calibration against regional watersheds: . Remote Sensing - Landsat MSS, TM or SPOT for Land Cover Component of SCS-CN - Aircraft Photography - stereo for elevations to develop slopes detailed structure, roughness estimates, storage . Airborne Laser Mapping - topography o GIS . Manage data sets and merge for parameter definition . Digitize/manage soils, stream network/contours . Use region growing for time-area curves and centroids from digitized contour or USGS/DMA Digital Terrain Tapes . Allow easier analyses of impacts of different strategies . Develop isohyetals from point rainfalls . Improve quality control for computational techniques . Provide breadth of outputs; color maps/plots, tables . Allow easy watershed segmentation to better represent spatial variability

OBJECTIVE	APPROACH	ISSUES/INFORMATION REQUIREMENTS	ROLE OF INFORMATION SYSTEMS & REMOTE SENSING
		. Kinematic Wave for Urban - slopes, roughnesses, connectivity, details of drainage structure o DWOPER - channel network structure, cross-sections, slopes, lengths, roughnesses, local inflows	o If user runs Hec-1 using several gauged watersheds for calibration: . Remote Sensing in combination with GIS as above to: - Define similarity among watersheds - Enhance optimization of parameters . Information Systems (archieved) for stream flows - WATSTORE, Reachfile, USDA Water Data Laboratory - Digital format DCP Data from Corps of Engineers
		o STORM - percent of imperviousness, depression/detention storage, runoff coefficients for losses	o If user runs DWOPER as option for Routing . Remote Sensing . Landsat MSS, TM or SPOT or Aircraft Photography (digitized) for: - Channel network - Distribution of land cover to aid in estimates of local inflows along streams . Airborne Laser Mapping - Channel cross sections . Aircraft Stereo - channel cross sections and aid to estimates of roughness coefficients . Helicopter Video - aid in roughness estimates . GIS . Use digital terrain and region growing capabilities to define areas contributing local runoff along channels . Manage/merge data sets as outlined above o If user runs STORM for small urban watersheds . Remote Sensing . Above systems for percent of imperviousness from land cover classes . GIS-definition of coefficients
3. Use mathematics/models for <u>real-time flood forecasting</u> to serve as inputs to water control decision-making	Real-time rainfall (snowmelt) and current watershed conditions input to: HEC1-F DWOPER operated in similar approach as outlined in (2) with real-time behavior of gauged watersheds used to estimate hydrograph parameters for ungauged areas	o Real-time access to rain guages and steam guages: Translate point measurements to spatial rainfall distributions and project to future time steps o Use gauged streamflows in a small set of subwatersheds to estimate hydrograph parameters for all ungauged watersheds o Run HEC1-F and, frequently, DWOPER using above inputs o Losses, Snyder or Clark parameters, and DWOPER channel conditions as outlined above in (2)	o Rainfall . DCP network . DCP network interfaced with radar . GIS - convert point to isobyetal then region growing to develop estimates for array of grid cells . In arid or semiarid regions use AVHRR vegetation to estimate an "index" of initial moisture of regional scale: GOES indications of surface temperature as a second "index" . Soil moisture probes with DCP communications interfaced with GIS . Weekly aircraft microwave flights (in future) for estimates of soil moisture; interface with GIS . Landsat MSS/TM or SPOT for land cover interfaced with digital soil and terrain data to define similarity among gauged/ungauged areas . GIS - manage the array of data sets that, for this problem, vary both with respect to time and space during the event o Other Remote Sensing/Information Systems issues outlined above in (2) apply to the real time problem

OBJECTIVE	APPROACH	ISSUES/INFORMATION REQUIREMENTS	ROLE OF INFORMATION SYSTEMS & REMOTE SENSING
4. Use mathematical models to estimate the <u>stages</u> along a stream network that result from a flood or series of floods: o For studies using estimated runoffs from real or simulated rainfalls o For real-time decision-making using: . HEC1 - F/DWOPPER estimates . Possible Reservoir Release Rates	Output of (2) or (3) serves as input to HEC-2 o Can simulate depths for one or several flows o Can simulate depths for a large number of events to produce a stage-frequency series and stage-discharge relations	Same as (2) or (3) Role of channel roughness and cross-sections becomes increasingly important on accuracy	Issues on Remote Sensing and Information Systems related to (2) and (3) carry forward to this problem of stage estimation o Remote Sensing . Airborne Laser Mapping - valuable cross-sections data, especially when there is significant overbank flow. . Low Altitude Stereo-Pairs - detailed cross-sections. . Helicoptor Video - aid in roughness estimates: if low altitude, should have quality or reliability approaching USGS Water Supply Paper 1849 for along-stream variations. o GIS . Manage cross-sections and control computational sequence - through vector based link-node controller
5. Develop estimates of economic damage vs. stage for reach <u>(Stage Damage Curve</u>)	Output of (4) interfaced with estimates of damage as a function of depth of water SID or DAMCAL and EAD	o Cross-section detail of (4) o Location of structures and their ground floor o Relation showing economic loss as function of depth of water for each structure category o Critical, but often massive, data set	Topography as outlined in (4) o Remote Sensing . Englarged SPOT Photographic Products for structure type and count (frequently location) . Low altitude photography (stereo) for structure type, location and local ground elevation . Helicoptor video for structure detail . Airborne Lasser for location and ground elevation o Information Systems . Use small optical scanner interfaced with PC to digitize tax records and convert to ASCII files . GIS - Digitize structure location and maintain information files - Relate address files to spatial data planes - Interface stage data of (2) with spatially distributed structure/damage data to produce changes in reach stage-damage as each structure is impacted

cover differences that must be considered. The GIS is needed to define differences in watershed shape, topography and soil conditions.

The networking capabilities of information systems can be very important aids in developing flood frequency series from stream gauging records. The archived streamflow data of USGS (WATSTORE) and the USDA Water Data Laboratory can be valuable and can be directly accessed by the hydrologist's personal computer through a modem.

Further, the EPA Reachfiles can be directly accessed and can provide considerable information about conditions upstream from a gauge. The USGS WATSTORE system is limited at present because it does not maintain direct access to hydrographs at time increments of less than one day.

5.2 *Use of Models to Estimate Runoff from Single Events and to Estimate Stage Along a Stream Network*

The thrust of this discussion is the use of HEC-1, or HEC-1F in combination with a channel routing component such as DWOPER, to compute the hydrograph produced by a real or synthetic storm. The hydrographs may be inputs to subsequent analyses, or, in the absence of stream gauging records, they can be used to develop a synthetic flood frequency series.

First, remote sensing and GIS can be used to develop estimates of the rainfall excesses required for HEC-1. These tools are best suited when the SCS Curve Number option is adopted by the user, if the user recognizes the sensitivity trade offs illustrated by Figure 2.12. Further, region-growing capabilities in many GIS's can be used to isolate the watershed boundary if the behavior indicated by Figure 2.11 is recognized. This region-growing capability can be very attractive when there are several watersheds involved or when a structure under study may be moved up or downstream several times during the decision-making process. The elevation data should be in a digital format to be of greatest value. The USGS 7-1/2-minute digital terrain tapes with a 30-meter resolution are sometimes available for the area of interest.

When the USGS data are not available, the digitizing modules of many GIS's are efficient enough to allow the digitizing of contours from 7-1/2 minute or larger scale maps. The digital traces of the contours can then be interfaced with region growing capabilities to define grid-cell elevations as illustrated by Figures 2.8, 2.9, and 2.10. If better than 1:24,000 accuracy is required, aircraft stereo pairs or airborne laser mapping techniques can be used to develop the elevation data.

If the Snyder approach to hydrograph definition is selected, the distance along the stream to the centroid of the watershed can readily be determined with the GIS. The centroid can easily be determined with a grid cell data base by taking moments about an X and a Y axis located outside the watershed boundary. Line following along the vector trace of the stream can move up from the watershed outlet and list the distance to the point opposite the centroid. Also, it should be possible to relate the slope/storage and peak discharge coefficients to watershed characteristics that can be measured by remote sensing techniques. The Denver Metropolitan Council of Governments, for example, used stream flow records from their region to develop estimates of these coefficients in terms of percent of imperviousness.

If the Clark time-area curve option is selected for hydrograph definition, region growing and, in parallel, flow path delineation as illustrated by Figures 2.4-2.8 can be used to develop the required times of travel as shown in Figure 2.9. The utility of these travel times and sub-basin delineations would have to be analyzed in terms of Figure 2.11. If urban watersheds were

involved, it should be possible for HEC to modify the Clark method along the lines of ILLUDAS which uses time-area curves for the impervious and pervious portions of the watersheds.

With a good GIS, the Corps of Engineers could use remote sensing to separate the pervious and impervious segments of the watershed and then apply region growing to generate the necessary time-area curves. Further, the remotely sensed land covers could be used to estimate the overland-flow roughness coefficients needed for flow times if the area is relatively small.

If HEC-1 is calibrated against hydrographs collected from watersheds in the region, remote sensing and GIS can be used to quantify similarities among the watersheds. Again, such GIS definable quantities as curve number, slope, shape, channel lengths/structure, etc., can form the basis for transferring data from one basin to the other.

HEC-1 defines a hydrograph at the outlet of a watershed. If several subwatersheds are involved or if the consequences of a hydrograph at some point downstream must be assessed, a channel routing model must be interfaced. DWOPER is an example of such a model and is representative of those state-of-the-art approaches that use the differential form of the complete continuity and momentum equations. To be of any real value, the results of DWOPER must be based on realistic channel cross sections, roughnesses and local inflows.

Aircraft stereo pairs or airborne laser mapping can provide the required accuracies. ***Figures 5.1A*** and ***5.1B*** are examples of stream cross sections obtained with an airborne laser system by the Waterways Experiment Station. The Corps' evaluation of airborne laser mapping produced cross sections that were within five inches of surveyed profiles in open areas and with 19 inches in forested areas. Thus, cross-sections defined by a future operational aircraft laser survey could be of significant value, especially if the images are obtained during low flows and there are significant over-bank flows.

Local runoff entering along the stream network can be significant. The region-growing techniques discussed above could be extremely valuable if large numbers of routing reaches are involved. The discussions associated with HEC-1 apply to the analysis of these watersheds distributed along the stream network.

When the results of HEC-1 or HEC1-F have produced a peak discharge, HEC-2 is used to compute the water surface profiles along the channel system if a steady-state condition approximation can be accounted. An alternative is to use a dynamic model such as DWOPER and interpolate along the transient water surface profiles to define the critical stages. Either way, all of the discussion associated with HEC-1, HEC1-F and DWOPER is applicable to the water surface profile problem.

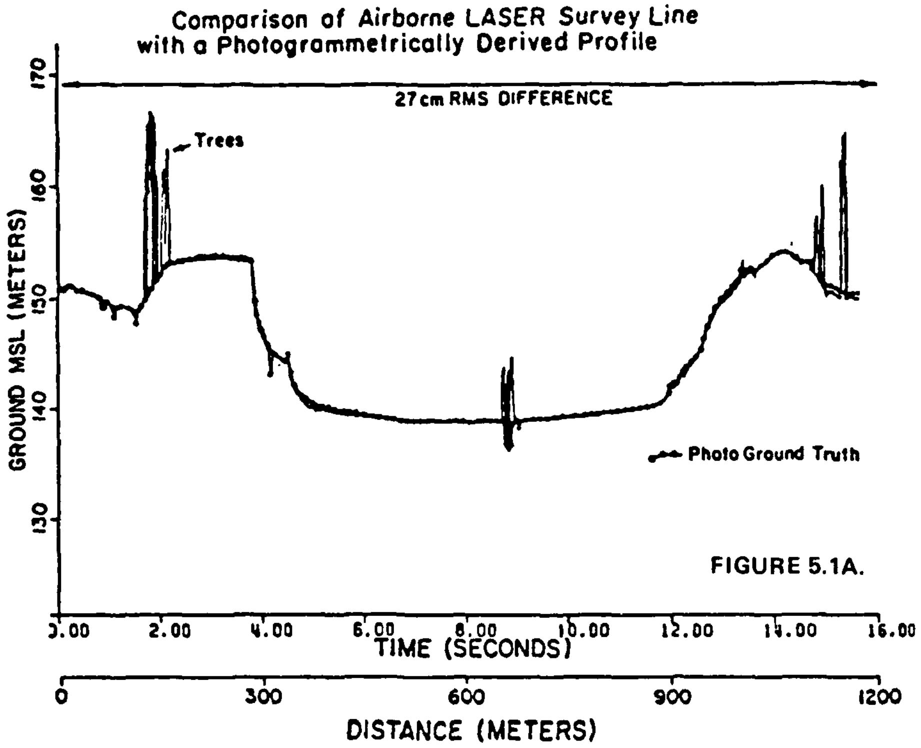

FIGURE 5.1A.

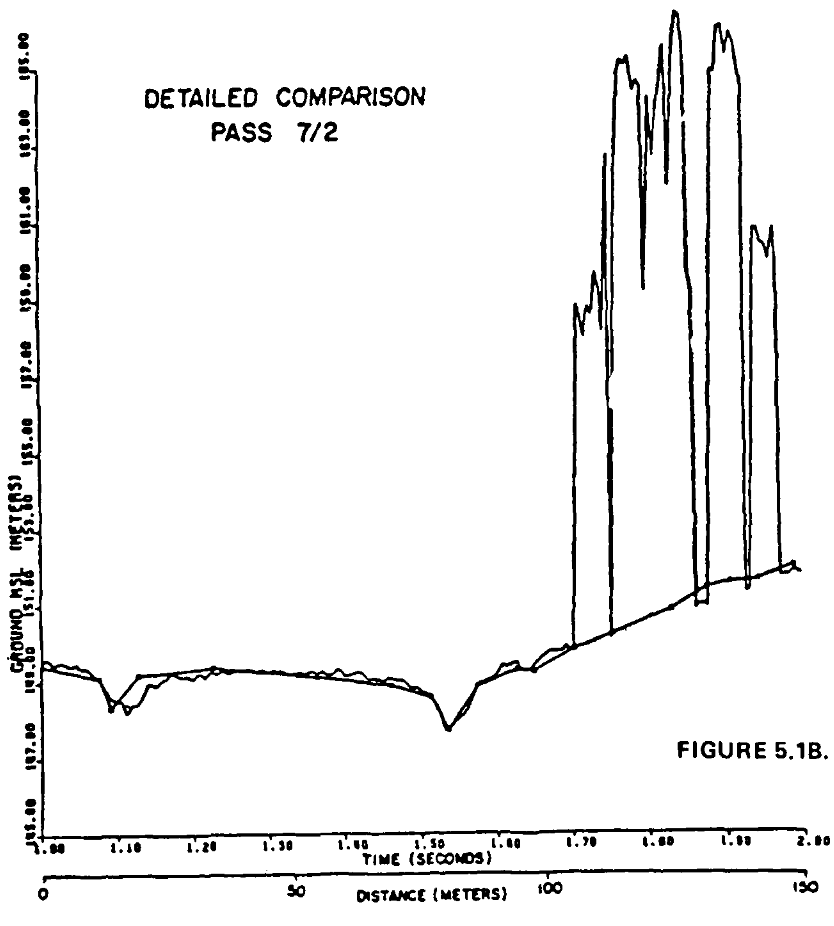

FIGURE 5.1B.

FIGURES 5.1A / 5.1B. Comparisions of laser reference profile for stream valley.

The water-surface elevation is the key driver in an array of decision-making scenarios encountered by Corps personnel. Because these elevations are tied to economic projections and flood damage losses, they must be extremely accurate. In this situation, the role of the spatial distribution of cross sections and roughnesses become critical. The GIS can be invaluable in the management of the data. Airborne laser mapping or stereo pairs appear to be the most promising options for defining the cross sections. Low-altitude aerial photography or color video could be used to locate obstructions and to aid in estimating the roughness coefficients.

5.3 *Real-Time Flood Forecasting*

The discussion presented above concerning HEC-1 and DWOPER applies also to real-time forecasting with HEC1-F and DWOPER. The complexity of real-time forecasting is increased by the additional requirement to calibrate to current conditions and project the operation of the models into a series of future time steps. This section includes discussion of these "real-time" aspects.

The first problem centers on the temporal and spatial distributions of the rainfall. The capabilities of Radar and interfaced reporting rain gauges are presented elsewhere in this report. Use of a GIS to manage and convert point measurements to cell-by-cell estimates using region growing could be extremely valuable. As in Oklahoma, tracking rainfall before it actually arrives on the watersheds of interest could be valuable in providing additional time for initial condition calibrations.

In arid or semiarid regions, AVHRR and GOES can be developed into tools that would provide important relatively broad "indices" that reflect initial conditions. For example, weekly tracking of a vegetation index could provide a indication of the general state of the soil moisture. Such an approach would not attempt to estimate the real volume of moisture in storage, but rather, would aim at a series of indicators ranging from very dry to very wet. Surface temperatures obtained from GOES might be used in conjunction with AVHRR to develop some form of watershed moisture indicator.

An indication of the role of soil moisture on the partitioning of rainfall into infiltration and excess is illustrated by *Figure 5.2*. Figure 5.2 presents the results of a series of numerical experiments that used the Richards equation. An array of rainfalls were applied to a series of soil columns under various moisture conditions to define infiltration rates and rainfall excesses. The strategy was to run the Richards model with an initial soil moisture of 0.25 cm/cm. The initial soil moisture was then increased and decreased away from the 0.25 and the runs repeated. Figure 5.2 shows the changes in the volume of rainfall excess that results if the actual initial soil moisture was 0.25 cm/cm, but the hydrologist incorrectly estimated it to be the indicated value.

Although admitted theoretical, this type of simulation is important if we are to properly assess the requirements for remote sensing or other instrumentation. Surprisingly, the experiments of Figure 5.2 indicate that we can accept errors in our estimates of initial soil moisture when we are dealing with larger storms and, as a consequence, expect relatively small percentage changes in the volume of runoff. At the same time, small errors in the initial soil moisture estimates produce large percentage changes in the volume of estimates produce large percentage changes in the volume of runoff when small, high frequency storms are involved.

Thus, as the Corps of Engineers expand their role in day-to-day forecasting for overall water-resource management, the need to define the daily soil moisture for use at the beginning of the non-flood producing rainfall will increase. Although microwave remote sensing continues to be an optimistic topic of research, low-level aircraft gama-ray flights and *in situ* measurements are the only operational approach currently available. Use of the soil moisture probes developed at CRREL attached to a DCP communications system is quite reasonable. Measurements from a network of these probes could be input to a GIS where region growing techniques could be interfaced with soil texture data to produce estimates of spatial distribution of soil moisture.

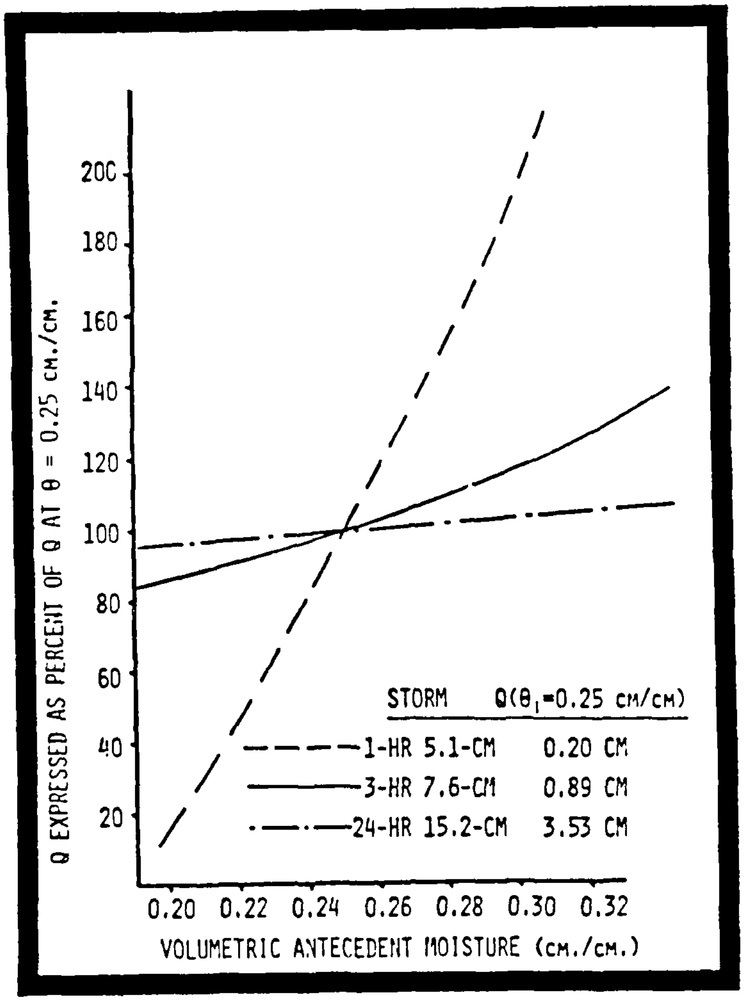

Figure 5.2. Percentage variation in excess rainfall as function of error in estimate of antecedent moisture.

5.4 Stage Damage Relationships

To estimate stage-damage it is necessary to establish a relationship between the stages along a reach, as observed or estimated with HEC-2, and the associated economic losses. Ideally, the development of this relationship is based on a database that locates each structure with its first floor elevation and defines its damages as a function of depth of water. SID, DAMCAL and EAD are used in this task.

Appropriately processed (digitally) large scale SPOT satellite images could be used to establish the distribution of structure type along the streams. Indeed, direct digitizing of their locations with a minimum number of ground control points can be accomplished with SPOT imagery. Low-altitude stereo pairs or airborne laser mapping would be necessary to adequately define the floodplain topography and structure elevations. Helicopter video would be valuable in transferring stage-damage curves from structure to structure. The small optical scanners that are being introduced to support desk top publishing systems may be developed into tools to digitize tax records so that detailed property values and related information on file with the local governments can be incorporated into studies such as flood damage analyses. Several of these systems can translate a rather wide range of fonts into ASCII files. They are portable and the costs range from $2,000 to $6,000. Files created by such a scanner could be directly introduced into an information system.

The GIS is a very important tool in this task. In some instances, the number of structures is massive. Without a good GIS and data base, management of this information would be next to impossible. Multistage remote sensing coupled with ground sampling, census data, and scanned tax records could be developed into an approach that would reduce the time and costs associated with the development of the stage-damage relationships. This sampling approach would have to be interfaced with models such as kriging that describe spatial relationships. In this approach, large-scale remote sensing would be used to develop the general distribution of structure types. Higher resolution imagery would establish differences within structure types. Information from these two sources coupled with census data would then guide ground surveys that would sample subsets of representative structures.

5.5 *Quick Response Monitoring of Floods*

Imagery from a variety of Earth observation satellites has been successfully used for delineating flood-inundated areas. Under the experimental NASA Earth Observation Program, some of the early, successful applications of (Landsat data) were for flood monitoring or mapping, including major floods on the Mississippi River and the Indus River (Deutsch and Ruggles, 1974 and 1978). Concurrently, under a NOAA (National Oceanic and Atmospheric Administration) research program, NOAA satellite data were also used experimentally for flood applications, even though the satellites are used primarily for meteorology.

For practical application, however, flood data are needed by responsible officials in *minimum* time, if they are to be useful for protecting lives and property. They are also useful to flood forecasts and to verification of their hydrologic models. The experimental NASA program was not organized to provide the "quick response" needed under operational conditions during flood emergencies.

In 1984 the Landsat Emergency Access and Products (LEAP) Program of NOAA became operational. The program provides for prompt processing of acquired Landsat data over areas officially declared to be disasters by the U.S. Federal Emergency Management Agency (FEMA) for transmittal of "quick-look" gray-scale facsimile images to specified destinations in the field (Pepe and Lichy, 1983). But these photo products, which are black-and-white single-band prints of only fair quality are of limited use for flood monitoring.

As an adjunct to the NOAA program, the Water Resources Support Center of the U.S.A. Corps of Engineers, in cooperation with Satellite Hydrology, Inc., developed, tested and evaluated high quality Landsat MSS (multispectral scanner) data products in color analog form for delivery within 24-48 hours to the field office in which the flood was located. Ideally, post-flood assessments from satellites should be sufficiently prompt and detailed as to assist agencies to mobilize needed resources on a priority and rational basis. Geometrically rectified images of full or partial scenes are prepared to specified map scales. The data are digitally and (or) photo-optically enhanced in a variety of spectral renditions to best depict flooded areas. The procedures were first tested successfully on November 7, 1984, during a LEAP exercise conducted in response to flooding on the Vermillion River in Louisiana, U.S.A., (Lichy, Deutsch and Wiesnet, 1985; Soileau et al., 1985).

In late October 1985, Hurricane Juan, a weak storm with winds never exceeding 137 km/hr nevertheless caused more than 50 deaths and millions of dollars in flood damage from resulting torrential rains over coastal Louisiana, U.S.A. Landsat data could not be used because of extensive cloud cover. However, on November 6--a week after flooding had peaked--a cloud free, nighttime NOAA-9 AVHRR (Advanced Very High Resolution Radiometer) image was collected.

Processing of AVHRR thermal infrared (IR) bands 4 and 5 at the General Electric Digital Image Analysis Laboratory approximately three hours following the overpass yielded detailed, enhanced rectified images at 1:100,000 scale and revealed large, warm areas of ponded water and saturated soils. A dry season nighttime band 4 image collected June 4, 1985, was digitally combined with the flood image. Differences in anomalies on the resulting temporal composite were classified as flooded areas (Wiesnet and Deutsch, 1986). The data products were transmitted to the requesting office of the Corps of Engineers at New Orleans within 48 hours. The accuracy of the automated classification depicting the flooded areas was verified by field engineers (Soileau et al., 1985).

In a separate, but related, activity, the Kansas City District recently contracted with Earth Satellite Corporation to procure and process Landsat TM digital data for the Harry S. Truman Reservoir floods in October 1986. Subsequent to the flooding, the District office ascertained that Landsat TM imagery were acquired the <u>same</u> day as the reservoir crested (within one-hour of peak pool height). The Landsat TM imagery was GEOPIC™ processed and printed at 1:50,000 scale. With these images, and ancillary aerial photographs at approximately 1:20,000 scale, the District engineers were able to accurately determine maximum pool extent during this event.

From late 1982 to late 1983, some of the most severe flooding of record occurred in the Valley of the Parana River in South America. During a post-flood study of all available satellite flood imagery made by Wiesnet and Deutsch (1985) for the Organization of American States, an archival search yielded only a few usable Landsat images of the lower reach of the Parana River in Argentina. Furthermore, the NOAA satellite archives of Advanced Very High Resolution Radiometer (AVHRR) data were surprisingly sparse owing to infrequent coverage and frequent cloudiness, and yielded no usable imagery.

However, Coastal Zone Color Scanner (CZCS) data provided by NASA's Goddard Space Flight Center at Greenbelt, Maryland, contained cloud-free coverage over the lower Parana River Basin. Employing data collected by Nimbus-7 on June 24, 1983, near the peak of the flood, multispectral color images were prepared digitally. Three subscenes were then massaged to show a 700 km reach of the river in which flooding ranged in width from 20 to 70 km in the Valley of the Parana (Wiesnet and Deutsch, 1985). The CZCS had never before been used in flood studies.

Although the Nimbus-7 CZCS was designed primarily for oceanographic applications and the NOAA-8 and -9 AVHRR for meteorological applications, imagery from both--with their wider swath and greater frequency of coverage--can supplement or substitute for the higher resolution Landsat MSS data. Both can be digitally and photo-optically processed immediately after acquisition and provide a quick response data base needed for emergency operations (Wiesnet and Deutsch, 1987).

The new SPOT satellite and the Thematic Mapper on Landsat, both operational, can provide data adequate for mapping of floods at scales as great as 1:24,000. Radar imagery from Seasat and the Space Shuttle has a demonstrated capability not only to detect areas of flooding, but to penetrate clouds and forest canopies; Seasat and Space Shuttle acquired radar data are very limited, however, and not available on an operational or continuing basis.

Operational, quick-response flood monitoring is well within the current state-of-the-art. An effective program should provide for real-time acquisition of data from existing satellites with appropriate Earth-observation sensors, immediate processing and enhancement of the imagery, conversion to analog and image map formats, and prompt transmission of custom data products to officials in the flood area.

5.6 *Determining Interception and Depression Storage and Measuring Surface Water Distribution*

The geomorphology, or physiography, of a basin provides the hydrologic engineer with information on interception and relatively large storage systems such as ponds, wetlands, broad floodplains and playas. The common method of estimating the consequences of storage is to examine the best available topographic map, but Landsat TM or SPOT imagery provides details of drainage and local depressions in far greater spatial detail than most maps. Side-Looking Airborne Radar (SLAR) images from aircraft are remote sensing tools that may reveal precise details of basin topography, far exceeding the detail on topographic maps. Indeed, the jungle areas of the Amazon basin were mapped by SLAR because of the ever present cloud cover. Commonly, combinations of radar images and Landsat or topographic maps provide better understanding of the basin than each alone. The extent of existing surface water in the open and in forested areas may provide a measure of the current "hydrologic condition" of a basin. Multispectral sensors such as the MSS or TM on Landsat and NOAA AVHRR all provide an ability to map surface water. The Corps, for example, has used Landsat MSS data to inventory dams in the U.S. Water in forested areas, however, is not as readily mapped with multispectral or thermal infrared techniques. Radar (active) or passive microwave data may strongly assist because of the "relatively" unique emissivity characteristics of water, i.e., water is almost a "blackbody" in comparison to the variable "graybodies" which surround surface water areas.

5.7 Estimating Precipitation, Snow Cover and Snowmelt, Evapotranspiration, and Soil Moisture

Precipitation is obviously a key parameter in any system which hopes to model the hydrological response characteristics of any region. Precipitation rate and amount information alone commonly determines the potential for flash floods. Rain gauge networks are commonly too limited to provide an adequate map of the spatial and temporal distribution of precipitation. Satellites and/or radar have demonstrated the capability to provide spatial locations and limits of rain areas. Intensity of rainfall appears best defined through the combined use of rain gauge, radar and/or satellite sensor data.

Meteorological satellites such as GOES are used to estimate precipitation. GOES produces a 1-km resolution thermal image every half hour, day or night. Therefore, half hourly rainfall rates may be developed. The primary NOAA locations where these estimates are made are: The World Weather Building, Suitland, Maryland; the Severe Storm Warning Center in Kansas City, Missouri; and at the NOAA/NESDIS Receiving Station at Redwood City, California. At present, rainfall rates and total amounts are estimated operationally for convective storms and hurricanes only. These data are available during and shortly after major storms.

Remotely sensed estimates have the advantage that the data are contiguous over the entire basin and are precisely timed. Isohyetal maps can also be prepared either retrospectively or in near-real time for hydrometeorologic analysis. The basis for the satellite precipitation estimates lies in the fact that the observable cloud-top temperatures are a function of cloud height which is related to precipitation. Other meteorologic criteria such as overshooting tops, are also utilized in estimating precipitation amounts. Excellent references may be found in Deutsch, Wiesnet, and Rango (1981).

NWS radar is also an excellent source of information on precipitation. This remote sensing tool is ground based. It provides excellent data on individual storm duration, intensity and droplet size. It is especially important over coastal ocean areas or large lakes such as the Great Lakes, where precipitation gauges are nil.

In critical areas, where high intensity rains deluge small "flashy" urbanized basins, (e.g., the Los Angeles area) event-precipitation-gauge networks have been used in combination with a satellite or other telemetry system to facilitate warnings. These gauges have proved very effective as each mm of rainfall is recorded and transmitted in near-real time rather than at hourly or six-hourly intervals. In those basins where the receipt of real-time data are critical, event gauges may be coupled with satellite or other Data Communication Systems (DCS's) and are effective for near-real time forecasts and warnings.

In EarthSat's CROPCAST rainfall estimation system, meteorological satellite data are analyzed in the visible .5-.7 um and the thermal 10-12 um bands from the GOES, METEOSAT, or GMS geosynchronous meteorological satellite systems. The visible .5-.7 um data are primarily used to screen isolate cirrus (high, ice crystal cloud) layers from the rain-producing clouds with extensive vertical layering and/or development. The visible and thermal infrared sensors can be enhanced by the use of microwave data from the NOAA TOVS and the DMSP SSM/T_2 (water vapor sounder) and/or the SSMI microwave imager (visible images plus moisture images). These latter sensors provide a useful measure of the precipitable water in the atmospheric profile (precipitable water is in essence an increase of the total amount of water that could be derived from a specific air mass if it all could be extracted).

Snow is hydrologically significant in many river basins. Measurement of the snow pack provides information on water stored in the basin in the form of snow, and it provides a basis for improved discharge estimates during snow melt or thaw periods. Snow data is difficult to acquire, requiring survey teams and strenuous work commonly in remote, difficult-to-access sites. However, imagery from the NOAA polar-orbiting satellite has been used for mapping the area of snow cover in selected river basins by NOAA/NESDIS since 1974. Landsat temporal composites showing phased snow melt reduction of the Sierra Nevada snow pack were published in 1976 (Wiesnet and McGinnis, 1976). "The use of satellite data for snow cover reconnaissance is becoming more widespread in the western United States and in the Sierra Nevada in particular. A cost comparison analysis between satellite and conventional aircraft measurements indicates that the cost of the NOAA satellite snow measurements is less than 1% of the cost of aircraft surveys." (Matson and Parmenter-Holt, 1985).

Despite their useful capability to provide snow cover data, neither Landsat nor NOAA nor GOES sensors can provide data on snow depth. NOAA/NESDIS has prepared river basin snow maps from NOAA and--later--GOES satellite image maps since 1974, using photo-interpretation techniques and a Zoom Transfer Scope (Matson and Parmenter-Holt, 1985). For small basins, Landsat images have been used in similar fashion. Repeated mapping of snow covered area for the entire basin or for various elevation zones permits basin snow cover depletion curves to be developed for year-to-year comparison or for modeling (Rango and Martinec, 1979), or for predicting snow melt runoff (Moravec and Danielson, 1980). Digital techniques of snow cover (Merry and Miller, 1987) have also been worked out and are particularly valuable in merging data sets such as snow cover and elevation or slope digital data.

Experimental studies of snow depth remote sensing using passive microwave have been done by Rango et al. (1979) in southern Alberta and Saskatchewan, Canada, using the Electric Scanning Microwave Radiometer (ESMR) data from Nimbus 6. Over large, flat, homogeneous areas, significant (95 percent) regression relationships were developed between snow depth and microwave brightness temperatures.

The Landsat TM also has a 1.55 um channel, which permits snow to be discriminated from clouds, as snow has only a slight response in this portion of the spectrum. This snow-cloud discriminator band is planned for future NOAA satellites.

Evapotranspiration is a process that involves atmospheric, soil and plant processes. Remote-sensor contributions to estimation or modeling of evapotranspiration come from a mix of vegetation type mapping using traditional multispectral data sets from the Landsat, SPOT, NOAA/AVHRR; thermal infrared data from Landsat TM or NOAA/AVHRR thermal-infrared sensors, and observations of winds, humidity and temperature from ground sensors. The vegetation-type distribution will provide an opportunity to model transpiration factors; the thermal-infrared observations of apparent surface temperature may be able to provide a concurrent view to infer the distribution of the variation in the rate of transpiration across the ensemble of vegetation mapped with Landsat, etc.

Moisture in the soil, especially in the upper layers of the soil profile, represents an important and difficult-to-determine variable in hydrology. Schmugge et al. (1981) have discussed *in situ* and remote-sensing methods of determining soil moisture (*Table 5.2*). Point and point-profile soil moisture data are rare. Gravimetric (oven-drying), nuclear (neutron-scattering), gamma-ray attenuation, electromagnetic (electrical resistivity), tensiometric (soil-water tension) and hydrometric techniques are *in situ* techniques used in the field.

TABLE 5.2: COMPARISON OF REMOTE SENSING APPROACHES FOR DETERMINING SOIL MOISTURE

APPROACH	*ADVANTAGES*	*LIMITATIONS*	*NOISE SOURCES*
Thermal Infrared (10-12 um)	High resolution possible (400 m)	Cloud cover, limits frequency of coverage	Local Met conditions
	Large swath		Partial vegetative cover
	Basic physics well understood		Surface topography
Passive Microwave	Independence of atmosphere	Poor spatial resolution (5-10 km at best)	Surface roughness
	Moderate vegetation penetration	Interference from man-made radiation sources, limits operating wavelengths	Vegetative cover
			Soil temperature
Active Microwave	Independence of the atmosphere	Limited swath width	Surface roughness
		Calibration of SLAR	Surface slope
	High resolution possible		Vegetative cover

Experimental techniques in remote sensing are now focused chiefly on the thermal infrared and microwave portions of the electromagnetic spectrum. Experiments using spectral reflectance or multiband approaches have encountered the difficulties of soil texture, organic content, surface roughness, geometry of illumination and spectral reflectance of the dry soil (Jackson et al., 1978).

Experiments at the U.S. Water Conservation Laboratory in Phoenix, Arizona, has demonstrated that the diurnal range of temperature is a function of soil moisture (Idso et al., 1975). However, the relationship ranged widely according to soil type and meteorological conditions. Nevertheless, Schmugge et al. (1978) were able to derive a single relationship for all soils studied by expressing the moisture values as "percent of field capacity."

Although passive microwave experiments on soil moisture (Table 5.2) have been carried out for decades, no operational techniques have as yet been produced. Passive (and active) microwave energy has the great advantage of being able to penetrate cloud cover, thus making it a very desirable tool. The DMSP SSMI is scheduled to provide some type of soil moisture estimates from an algorithm in an operational mode, but the accuracy of the technique has yet to be established.

Soil moisture can also be remotely sensed by the airborne gammaray technique discussed in the previous section. In fact, it is a by-product of the system, as summer calibration flights must be flown to assess the "background" moisture values during the non-snow condition.

The natural gamma radiation constantly being emitted by the radioisotopes in the soil is attenuated by the near-surface moisture in the soil. Once a flight line is calibrated using ground truth soil moisture data, the airborne technique can be used to infer soil moisture in the uppermost eight inches of soil during snow free periods. Carroll's (1986) tests indicate these measurements have an RMS error of 3.9 percent soil moisture and less than a one percent bias. These figures are based on airborne radiation and ground-based soil moisture measurements collected over 155 snow-free calibration flight lines (Carroll, 1986).

The NOAA Remote Sensing Hydrology Program collects soil moisture data for the same basins in which it collects snow water equivalent data (Section 5.7). These data are distributed in near real-time in SHEF to all NWS offices. However, RFC's typically archive the data in DATACOL, which can be made available to non-NWS DATACOL users. Special arrangements for data dissemination to non-NWS users are possible.

The gamma-ray technique is not without certain problems. As these flights are very low level (500 ft, a.g.l.), mountainous areas are not suitable. Airborne radioactive contamination can

affect results. Post-flight snowfalls can negate previous data on water equivalent. Changes in vegetation over a site can produce anomalous readings. Nevertheless, where conditions are uncomplicated, gamma-ray soil moisture and snow water equivalent measurements can provide valuable data to the operational hydrologist in near real time. This approach appears to be highly cost-effective.

5.8 *Recent Developments in Snow Cover and Snow Water Equivalent*

In December 1986, a Federal Users Group met in Denver, Colorado, to discuss the future of the National Weather Service (NWS) Satellite Snow Cover Mapping Program. The Soil Conservation Service, the Agricultural Research Service, the U.S. Army Corps of Engineers, the U.S. Geological Survey, the Bureau of Reclamation and the NWS Office of Hydrology were participants. The Office of Hydrology presented details of an operational Remote Sensing Hydrology Program to be based in Minneapolis, and a Working Technical Group and Policy Committee were formed. The implementation schedule is shown in ***Table 5.3***; attendees of the subsequent March 5, 1987, Policy Committee meeting are shown in ***Table 5.4***.

TABLE 5.3: FEDERAL INTERAGENCY REMOTE SENSING HYDROLOGY PROGRAM: ABRIDGED IMPLEMENTATION SCHEDULE

DATE	ACTION
1987 July	Cooperating agencies sign MOUs to develop and support Remote Sensing Hydrology Program.
1987 October	Cooperating agencies transfer FY 1988 funds to NWS for system procurement.
1987 October	NWS sign system procurement.
1987 October	Hire computer programmer/analyst.
1988 February	Take delivery of image processing system in Minneapolis.
1988 July	Transfer Milan Allen from Kansas City to Minneapolis.
1988 Feb-Dec	Develop and test software and real-time, satellite data interface procedures.
1988 September	Complete Five-Year Program Management Plan.
1989 February	Generate areal extent of snow cover maps in Minneapolis.

TABLE 5.4: MEETING PARTICIPANTS OF THE MARCH 5, 1987, POLICY COMMITTEE MEETING

POLICY COMMITTEE MEMBERS

NAME	AGENCY	TELEPHONE
Galen Hart	Agricultural Research Service	FTS 344-2822
Joseph Miller	Bureau of Reclamation	FTS 776-8307
Michael Hudlow	National Weather Service	FTS 427-7658
Edward Johnson	National Weather Service	FTS 427-7619
David Johnson	Soil Conservation Service	FTS 423-2843
Robert Shaw	Soil Conservation Service	FTS 447-3905
Harlan McKim	U.S. Army Corps of Engineers	FTS 836-4479
* David Wingerd	U.S. Army Corps of Engineers	FTS 272-8510
Harry Lins	U.S. Geological Survey	FTS 959-5712

* NOTE: David Wingerd attended in the place of Ming Tseng.

TECHNICAL WORKING GROUP MEMBERS

NAME	AGENCY	TELEPHONE
Alberto Rango	Agricultural Research Service	FTS 344-3490
David King	Bureau of RFeclamation	FTS 776-8322
Tom Carroll	National Weather Service	FTS 725-3039

OBSERVERS

NAME	AGENCY	TELEPHONE
L. Klingensmith	National Weather Service	FTS 427-7720
William Fecke	Soil Conservation Service	FTS 447-5424

In a position paper the Technical Work Group estimates that program implementation will have a one-time procurement cost of $356,000, and annual operation and maintenance costs of $212,000 (Federal Interagency Remote Sensing Hydrology Program, 1987, p. 1).

The U.S. Army Corps of Engineers has two members on the Technical Working Group:

Mr. Roger Gauthier
USACOE
Detroit District
477 Michigan Ave.
Detroit, MI 48226
Telephone: FTS 226-6751

Ms. Carolyn J. Merry
CRREL/USACOE
Hanover, NH 03755
Telephone: FTS 836-4307

The Corps also has two members on the Policy Committee:

Dr. Ming T. Tseng
Chief, Water Control/Qual. Branch
USACOE
HQDA (DAEN-CWH-W)
Washington, DC 20314
Telephone: FTS 272-8509

Dr. Harlan L. McKim
Remote Sensing Research Program
CRREL/USACOE
Hanover, NH 03755
Telephone: FTS 836-4479

Snow-cover mapping began as an experimental program in NOAA/NESS (now NOAA/NESDIS) in the late 60's and early 70's. In 1984 the effort was taken over administratively by the NWS National Meteorological Center at the World Weather Building in Camp Springs, Maryland. In fiscal year 1987, the NWS/OH has taken the lead in this program. The physical location of the satellite hydrologist performing the work since 1980 has been in Kansas City at the NWS National Severe Storm Forecast Center.

The Satellite Snow-Cover Mapping Program in Kansas City[5] consists of one satellite hydrologist, who generates snow-covered area maps for selected basins in the West. The output product is a binary snow covermap showing percent of basin snow cover (*Figure 5.3*). The maps are prepared from GOES visible 1-km resolution satellite imagery for each USGS catalogue unit selected for study. In 1986, a total of 133 snow cover maps were prepared for 196 basins (*Figure 5.4*). For details of the technique employed, the reader is referred to Allen (1986).

The primary users of the snow cover data are federal government agencies dealing with snow melt runoff: NWS River Forecast Centers, the Corps of Engineers, the Bureau of Reclamation, Soil Conservation Service, and the U.S. Geological Survey. Other users are State, Regional and local water authorities. The individual users have described their agency's applications in the Federal Interagency Remote Sensing Hydrology Program (1987) Position Paper.

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5/ See Table 5.3 for NWS/OH future plans for this program.

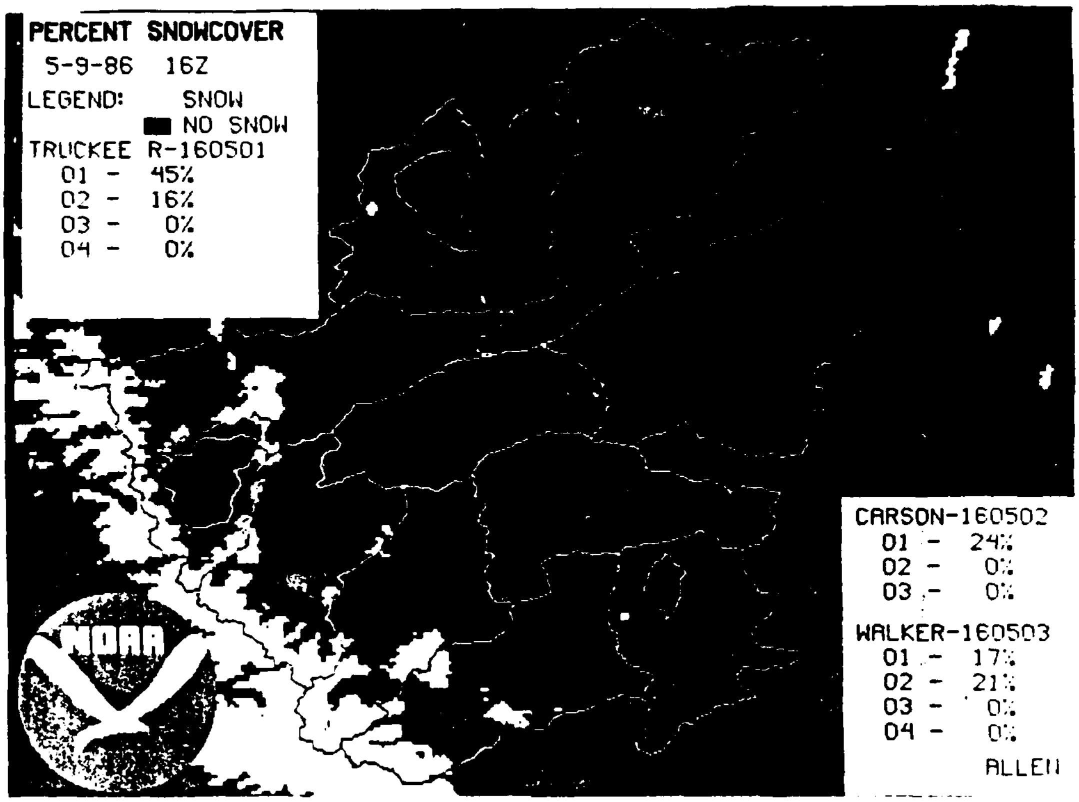


FIGURE 5.3. NOAA binary snow cover map showing percent of basin snow cover.

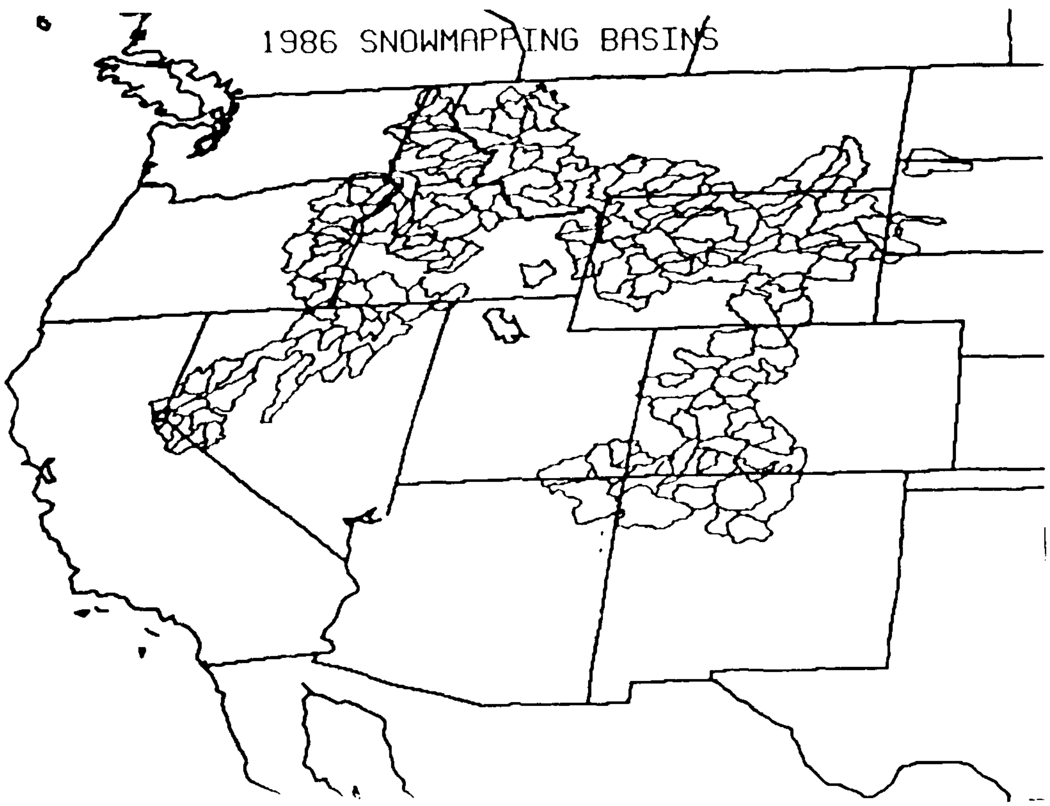


FIGURE 5.4. Map showing western basins mapped in 1986 NWS snow mapping program.

Douglas Speers, U.S. Army Corps of Engineers, and Charles Orwig, NWS, Portland, Oregon, say (p. 29-30):

> "Since the Columbia River is predominately a snow-runoff regime, accurate accounting of snow, both in terms of water equivalent and areal extent, is an important aid to river and water supply forecasting. While a less important parameter than water equivalent, areal snow cover is a variable that is needed for snowmelt calculations by the SSARR model as streamflow and system regulation forecasts are made during the annual spring runoff. Areal snow cover is also used subjectively as a factor in considering rate of refill of some reservoirs in the system."

They also say that in the SSARR model one option for simulating the status of snow during the runoff process calculates water equivalent quantities in several specified elevation "bands" throughout the snow accumulation and ablation seasons. The use of this model is replacing models that utilize the "snow cover depletion" option, which uses a specified snow cover depletion curve developed from historical data Figure 5.5. From an initial estimate of total seasonal runoff based upon multiple regression volume forecasts, the model calculates the corresponding snow covered area

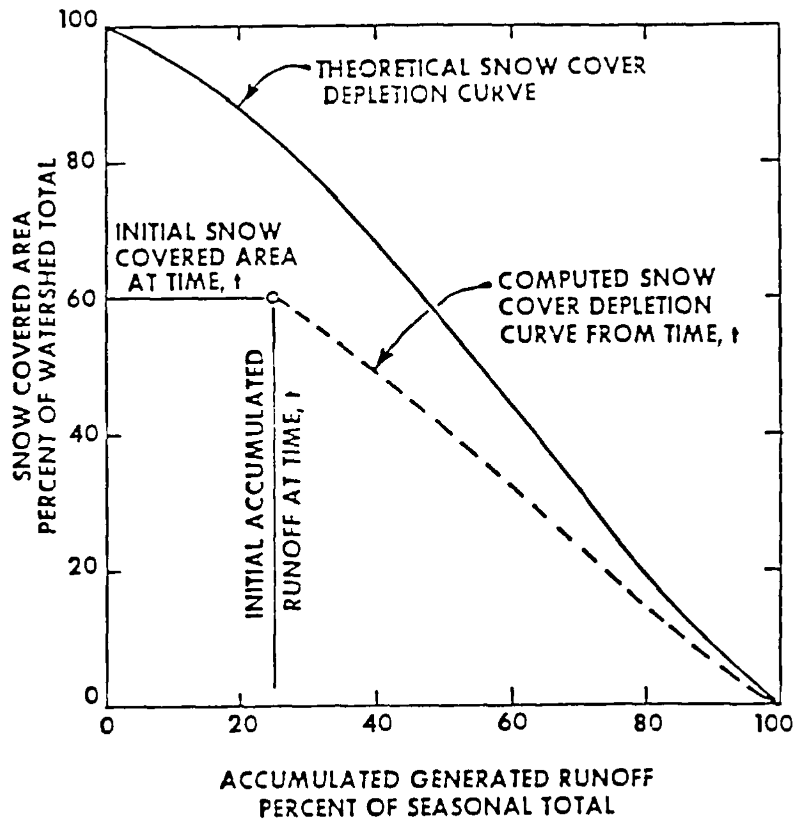


Figure 5.5. Snow Cover Depletion Curve

from this curve as runoff progresses. The snow-line elevation, which is needed for determining the air temperature available to produce snowmelt on any given day, and for tracking soil moisture and other model state conditions that are dependent upon snow-free versus snow-covered conditions, is then determined from a volume-area curve. Although the model computes snow cover and can function without physical observations, periodic checks on model performance are recommended.

For 30 years the need for snow cover observations has been considered so important that a program of fixed-wing aerial snow reconnaissance flights was maintained by the Corps. Flights made at 2-3 week intervals during the May and June over predetermined flight paths cover most important subbasins within the Columbia Basin. Snow-line elevation is recorded by visual observation and photographs at selected points. These flights cost about $20,000 annually. The cost of snow flights in Canada made by B.C. Hydro and Power Authority is not included.

When estimates of snow covered areas by GOES satellite remote sensing became available, they were incorporated into the ground-truth data base in addition to the snow flight data. The satellite information has generally been considered less trustworthy than the snow flight data owing to prior experiences with inaccuracy. Snow-line detection in heavily forested areas and the problem of adequate resolution (especially in small basins or when snow cover percentage is low) have caused difficulties in the past. Satellite snow-cover estimates have therefore, been considered a useful but not yet critical necessity for the snow-melt forecasting effort.

However, the recent work of NWS Satellite Snow Cover Mapping Program has improved the snow mapping products significantly. Further improvements in technology and greater experience and care in interpreting the satellite data should lead to greater reliance on satellite products in the future. When a new generation of satellites is launched with greater resolution, it is quite possible the fixed-wing snow reconnaissance flights could be eliminated.

David King, Bureau of Reclamation, Denver, says:

> "The areal extent of snow cover maps currently generated in Kansas City are used by various regional offices of the Bureau of Reclamation. The maps are used in conjunction with information that is received from the SCS, NWS, USGS, and other agencies to provide a qualitative check on the volume of runoff forecasts."

He also says that the Pacific Northwest Region found the snow cover maps to be very useful during the melt season and together with snow course measurements, visual snow line observations, and snow photography from aircraft. Their reservoir operations were enhanced because they could assess the accuracy of volume fore-

casts. The Pacific Northwest Region uses the satellite maps to verify the tracking of the SSARR model used by the River Forecast Center in Portland.

Regional users indicated that a more useful product would indicate not only snow cover, but also depth, water content, and melt rate. Incorporation of SNOTEL data and airborne snow water equivalent data would enhance the program.

Reclamation has a need for snow volume quantification and melt forecasting data and forecasts to operate their reservoirs. The better the data and forecasts, the better our operations will be." They fully endorse efforts to incorporate existing data into operational forecasting.

5.9 *Potential Opertional Benefit of Snow-Cover Mapping*

During the 1970's interest in the possible use of satellite snow cover data for improving snowmelt runoff forecasts was high. Several Federal and State water resources agencies participated in a project on the operational applications of satellite snow cover observations (Rango, 1980). When satellite snow cover data were tested in both empirical seasonal runoff estimates and short-term modeling, the results indicated that forecast errors could be reduced.

Water supply forecasting techniques utilizing satellite-derived snow-covered area data were developed for three basins in the Sierra Nevada of California. Forecast errors resulting from both conventional and Landsat snow-cover procedures are compared in ***Figure 5.6*** for the three basins.

Over a three-year test period the satellite-based approach reducted the average streamflow forecast error from 15 to 10 percent. On the Boise River in Idaho, associated modeling studies indicated that satellite snow-cover data could reduce short-term forecast error as much as 10 percent (5-day forecast) (Dillard and Orwig, 1980).

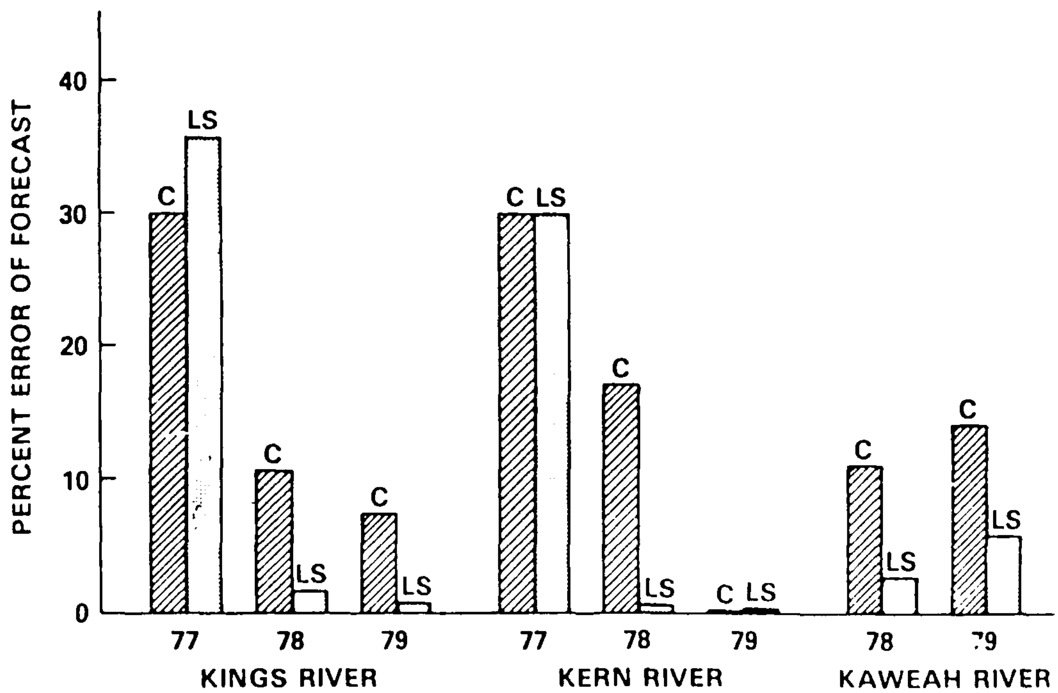


Figure 5.6: Seasonal snowmelt runoff forecast error using conventional (C) and Landsat snow cover (LS) procedures in the southern Sierra Nevada on May 1.

The snowmelt runoff model (SRM), which uses snow-covered area as its only snowpack input has been tested on 24 basins ranging in size from 0.77 to 4000 km^2 in 11 different countries (Martinec and Rango, 1986). Using this simple model, the average seasonal volume simulation accuracy was 97 percent and the average daily flow accuracy was 85 percent (Rango, 1986). The model simulations consistently indicated the importance of snow cover extent as an input variable.

Dr. Al Rango of USDA maintains:

> "In association with the operational applications of satellite snow cover observations project (Rango, 1980), an accompanying benefit/cost study was completed. Potential benefits from improved satellite snow cover based predictions of only one percent across the 11 western states were evaluated. It was found that benefits of 10 million dollars for hydropower and 28 million dollars for irrigation would result annually (Castruccio et al., 1980). The resultant benefit/cost ratio was calculated to be 75:1 (Castruccio et al., 1980). The only thing preventing realization of these significant benefits was the absence of an operational snow mapping facility to acquire and produce the snow cover data."

Dr. Bernard Shafer, SCS Portland, Oregon, (Federal Interagency Remote Sensing Hydrology Program, 1987, p. 36-37) discussed the importance of SCA to hydrologic forecasting in the Western U.S. He chose the 1983 record-setting runoff of the Colorado River to illustrate how SCA measurements from the NOAA satellite used conjointly with point data of snow water equivalent, temperature and precipitation from the SCS SNOTEL network could have been used to derive superior insights into this flood. That information would have been highly useful to decision makers trying to manage the heavy runoff.

Roger Gauthier, USCOE Detroit District, has cited potential applications to the Great Lakes (Federal Interagency Remote Sensing Hydrology Program, 1987, p. 38-39). "The Great Lakes Basin Hydromet Network Work Group, an ad hoc U.S. Federal (inter)agency study team, reported that improved water supply forecasting could provide benefits . . . in excess of $1 million annually."

Carolyn Merry, COE/CRREL, cited potential applications in the cold regions of the Midwest and Northeast (Federal Interagency Remote Sensing Hydrology Program, 1987 p. 39-40). She also stressed that "the real payoff for the Corps is the timely receipt of the areal distribution of water equivalent of snow data," and that the data provided be compatible with the Corps District's data base systems.

Linda Saindon of the U.S. Geological Survey addressed the application of SCA to hydrologic research. In the position paper (Federal Interagency Remote Sensing Hydrology Program, 1987) she noted the USGS Water Resources Division used products from the Snow-Cover Mapping Program in the USGS's Precipitation-Runoff Modeling research project to verify snow-accumulation and melt-process algorithms in the distributed-parameter snowmelt models being developed, as well as in the Ice and Climate research project.

5.10 *Remote Sensing of Snow Water Equivalent*

An Airborne Gamma Radiation Snow Survey Program is operated out of Minneapolis, Minnesota, by the Office of Hydrology of the National Weather Service (NWS). The airborne water equivalent measurements are used by Weather Service Forecast Offices (WSFO's) and River Forecast Centers (RFC's) for river and flood forecasting, water supply forecasts and Spring Flood Outlooks.

This is an operational program, providing real time snow water equivalent and soil moisture data to NWS regional and field offices in the Eastern, Central and Western Regions. A total of 1227 flight lines are flown in 23 states and 5 Canadian Provinces from January to mid-April 1987). Three aircraft are employed in the program. Two airborne gamma ray instrumentation packages are used.

Data gathered on these flights are used to assess:

1. The above ground moisture in the snowpack including snow, ice lenses, ground ice, and standing or free water,

2. The above ground moisture plus some measure of the soil moisture above field capacity, and/or,

3. The aggregate change in both the above ground moisture and the total soil moisture from a previously established measurement.

The airborne data are transferred electronically from the aircraft to Minneapolis. After an accuracy check, they are entered into SHEF, transmitted to the North Central RFC computer and sent to AFOS within two or three hours after the aircraft lands at noon or in the evening.

During a typical snow survey season, the two aircraft make about 1000 real-time airborne snow water equivalent measurements. Figure 5.4 showed the areas in the program as of 1 October 1986.

The technique of using gamma-radiation to determine water equivalent of the snow is widely discussed in the literature (Carroll, 1986; Gauthier et al., 1983; Peck and Bissell, 1973; and Wiesnet and Peck, 1972).

Carroll (1985) did a cost-benefit analysis of collecting airborne gamma radiation snow water equivalent measurements prior to the February 1985 flood at Fort Wayne, Indiana. Actual flood losses amounted to $4 million. Carroll (1985) has estimated that the flood damage prevented as a result of the early warnings and precise river forecast ranged from $700,000 to $2,400,000. The cost of the aerial survey in February 1985 in the Fort Wayne area was $7,700.

Requests to add new flight lines to the Program over specific river basins should be submitted through the NWS Regional Director to the NWS Office of Hydrology by June 30. This early notification allows time for background calibration flights to be performed during the summer to assess the background soil moisture response.

5.11 *Hydrologic Modeling of Urban Watersheds*

The hydrologic behavior of natural watersheds within a region is relatively consistent. For example, watersheds in the Piedmont have sufficiently similar hydrologic behavior to allow investigators such as F.F. Snyder (1938) to isolate a series of parameters and graphs that produce reasonable representations of unit hydrographs. As a result of this consistency, hydrograph parameters developed for several gauged subwatersheds within an area can be used to develop runoff hydrographs for the remaining ungauged subwatersheds. These hydrographs can then be routed to obtain estimates of basin runoff in real time using a model such as HEC1-F. The parameters defining Synder's unit hydrographs used in HEC-1 and HEC1-F center on the physiographic characteristics such as slope, storage and the interrelation between the watershed shape and the channel network. Land cover becomes a direct problem when loss rates are estimated for the runoff hydrograph. On the other hand, synthetic unit hydrographs for urban and suburban watersheds must incorporate the role of land cover if the timing and shape are to be realistic.

Because of the importance of land cover in urban watersheds, the immediate application of remote sensing becomes especially beneficial. Indeed, even the spatial distribution of the land cover categories is extremely important if the hydrologist must develop especially accurate estimates of urban floods. Fortunately, the combination of digital format remote sensing and geographic information systems has reached the state that allows hydrologists to conduct urban watershed analyses that were impossible only a few years ago.

While remote sensing capabilities offered by the Landsat series of satellites were recognized very early, satellite remote sensing to support routine hydrologic modeling for urban watersheds has not realized its early potential. Part of the problem has been with the perceived limitations of the 80-meter resolution of the MSS. Perhaps a more important problem was in the management of the Landsat data. The proponents of Landsat did not fully recognize the land cover was only one of several data sets required for the modeling of urban watersheds. The land cover could be defined in a matter of hours, but it still required many weeks to define the soil and topography and then "overlay" the land use onto these other data planes, there was little incentive to develop expertise in Landsat classification. The critical missing element needed for success was an efficient method for merging and managing the numerous data sets using a Geographic Information System (GIS).

Early development of HEC's Spatial Analysis Methodology (SAM) laid the base for integrating digital format remote sensing into urban hydrologic modeling. Subsequently, GIS capabilities have improved significantly because of the availability of smaller, more powerful computers supported by sophisticated graphics, and at the same time, the evolution of 10-, 20-, and 30-meter resolution satellites have eliminated earlier criticisms surrounding Landsat

MSS. The state-of-the-art in both satellite remote sensing and GIS technologies are at a point that their operational use in urban hydrologic modeling can become routine.

The 10- and 20-meter, and often the 30-meter, resolutions provide completely adequate discrimination required for hydrologic modeling in all but the smallest watersheds. These resolutions are such that the land cover distributions can be outlined from enlarged photographs and digitized directly into GIS without the need for specialized image processing systems. If large areas are involved and it is not practical to handle data manually, relatively inexpensive, quite easy to use, PC-based image processing systems can be employed. Even the problems of geometric registration for multiple data sets are now relatively easy to resolve with the interactive graphics and software of systems described in Section 4.0.

One of the hydrologic models that is quite attractive for use with remote sensing and GIS technologies is STORM. Percent of impervious cover is a key element in one option of STORM and the SCS Curve Number is the key in a second option. Jackson, Ragan and Fitch (1977) have established that even the MSS can be used to define imperviousness for STORM. Further, Jackson et al., outlined an approach that used Landsat on gauged watersheds to calibrate the runoff coefficients and detention storages on ungauged watersheds in terms of the percent of imperviousness. Other work by Ragan and Jackson (1980) showed that the MSS defined land cover categories were sufficient to compute the Curve Numbers required for the SCS based option in STORM. The experiments by HEC as summarized by Rango, Feldman, George and Ragan (1983) concluded that the Landsat MSS was applicable to a range of urban hydrology problems. The current 10-, 20-, and 30-meter resolutions with their opportunities for increased accuracies and, of equal importance, more traditional photographic qualities, make the use of satellite remote sensing with STORM a very attractive alternative.

There are two opportunities for adapting HEC-1 into an urban hydrologic model that is supported by remote sensing and GIS technologies. First, the Snyder hydrograph option can be modified for application on urban watersheds. The Denver Metropolitan Council of Governments adopted the structure of Snyder's synthetic hydrograph for their Colorado Urban Hydrograph Method (CUHM). The CUHM preserves Snyder's formulations, but defines the slope/storage and peak discharge coefficients in terms of the percent of imperviousness of the watershed. The use of satellite remote sensing to define imperviousness is well established. Thus, HEC could immediately undertake a study to define the Snyder coefficients following the approach of Denver. The result of this work would be a Snyder-centered HEC-1 that could be supported by satellite remote sensing to estimate the required percent of imperviousness. The current program, HYDPAR, is already used to translate into Snyder and other coefficients for HEC-1. Thus, it would be relatively easy to integrate an expanded set of formulations into the Corps' operations.

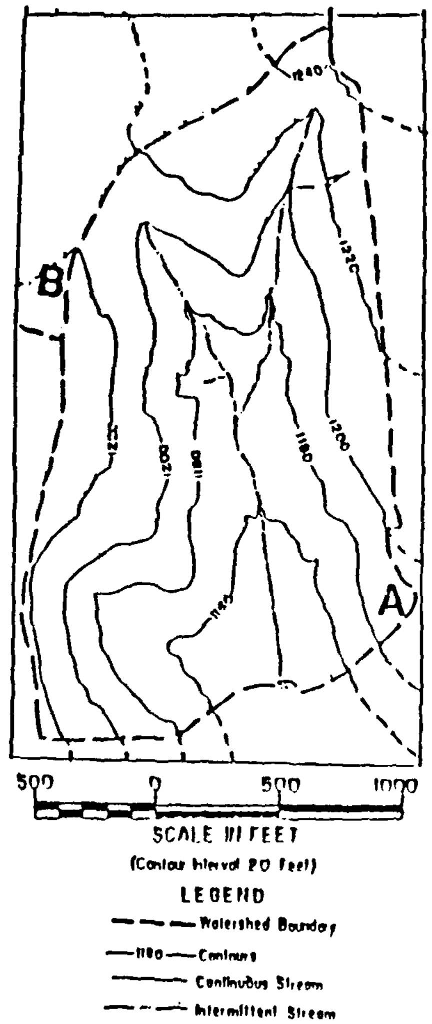
The second option in HEC-1 is the C.O. Clark approach to hydrograph definition. Clark's approach computes an instantaneous unit hydrograph (IUH) by developing a time-area curve by summing the travel times between isocrones. The time-area curve IUH is of considerable interest to urban hydrologists. Clark's concepts, for example, form the basis for the British Roads Research Laboratory (BRRL) method (Watkins, 1962) which, was revised for use in the US by Terstriep and Stall (1974). This latter method is known as "ILLUDAS."

Something like ILLUDAS could be integrated into HEC-1 as a variation of the Clark option for use in urban watersheds. As in ILLUDAS, the proposed approach would compute time area curves for the impervious and pervious sections of the urban watershed in order to better handle the loss functions. The identification and location of the pervious/impervious sections of the watershed could be accomplished with current satellite systems. Management of the locations would be handled by current GIS technology.

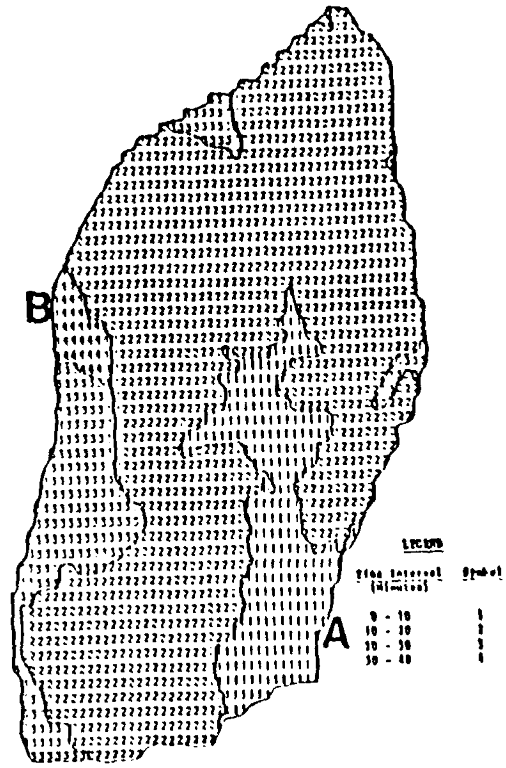
In the not too distant future it should be possible to use GIS capabilities to interface land cover and digital terrain data to "grow" watershed boundaries and automatically define the model parameters within the drainage basin. With this information and the fact that the storm sewers follow the street pattern, we should even be able to develop reasonable estimates of the storm sewer system that serves a developed area.

Recent developments that bring region growing and subsetting from the field of pattern analysis in the GIS make a Clark based approach reasonable. It is now possible to "grow" watershed boundaries directly from raw elevation data and then segment this watershed into subareas and link individual cells into a flow network. ***Figure 5.7*** from Sircar (1986) shows the contour map of a small USDA experimental watershed. This contour map was digitized and put into a GIS framework. Area filling and region-growing algorithms were implemented to assign each cell a slope, aspect, and connectivity relative to its flow direction to adjacent cells. A land cover was then overlayed to develop Manning roughness coefficients. These data allowed a detailed flow network to be developed which was reduced to the time-area curve shown by ***Figure 5.8***. This approach could be used for both the pervious and impervious segments of the watershed. The technique is especially attractive because it can be completely implemented on an IBM-PC/AT.

In summary, there are immediate opportunities to expand the use of remote sensing in urban hydrologic modeling. As recognized by HEC in the development of SAM, remote sensing and GIS must be fully integrated if meaningful advantages are to be realized. With remote sensing and GIS, the current structure of HEC-1, especially the Clark hydrograph option, can form the base for a model that could be a significant improvement over those currently used in urban hydrology.



(a)

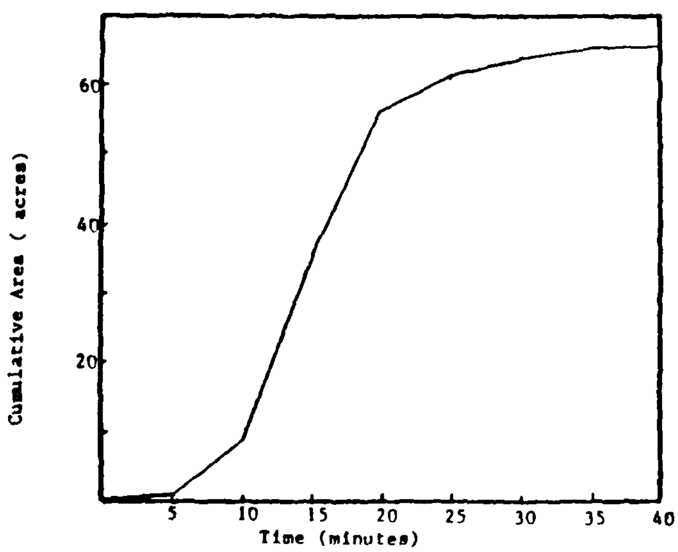


(b)

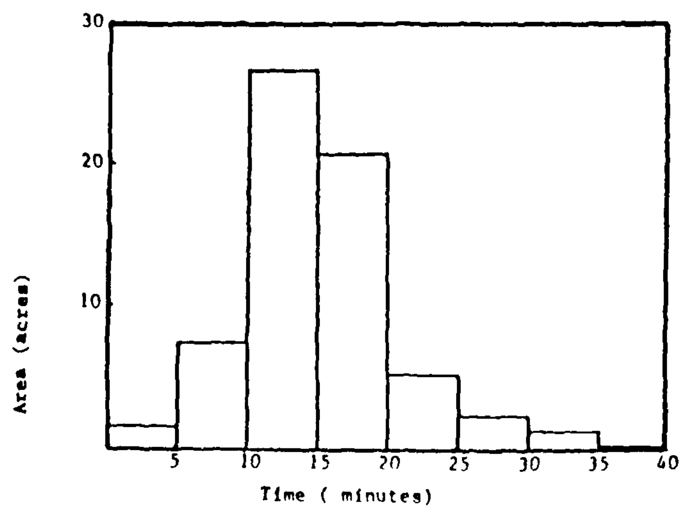
FIGURE 5.7. Illustration of the digital simulation of Time-Area Isochrons.

(a) Input contour line tracing derived from the original map of Treynor watershed, Iowa (source: USDA-*ARS, 1964*).

(b) An alphanumeric display of the 10 minute Time-Area isochrons corresponding to the watershed draining to the channel system shown in (a).



(a) Plot for Time-Area curve for the Treynor watershed.



(b) Plot of the Time-Area histogram at 5 minute intervals.

FIGURE 5.8. Plots depicting the results of Time-Area computations.

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5.12 *Example of Hydrologic Modeling Using ERDAS and a PC-Based GIS*

The Corps of Engineers currently have approximately 18 ERDAS Image Processing Systems, most of which are supported by IBM PC-AT's. The Corps also has a very large number of "off-the-shelf" microcomputers, many of which are either IBM PC's or are IBM compatible. Thus, the experiment described in this section is especially important because of its potential for immediate application by Corps of Engineers installations.

This section describes the use of an IBM-AT supported ERDAS image processing system to develop the land cover distribution of a watershed that falls within parts of four USGS 7.5 minute quadrangle sheets. The registered land cover is resampled to produce a 5-second Lat-Long. grid cell spacing using standard ERDAS image processing utilities. The resulting land cover data plane is then copied on to a floppy disk that can be used as input by any IBM compatible PC. The experiment to be described then uses the ERDAS generated floppy disk as the land cover data plane in a hydrologic modeling study conducted with a GIS operating on an "off-the-shelf" IBM-AT equipped with an EGA graphics board.

There are a number of companies that either offer GIS packages that operate on PC's or will begin offering such packages in the near future. ESRI has released portions of its PC-based ARC/INFO, GEOVISION, Geobased systems, Bausch and Lomb, Comarc, ERDAS, Terra-Mar, Integraph and Kork systems are examples of other suppliers. Because of its immediate availability to EarthSat and its consultants, the present experiment used a GIS developed by Ringan Associates of University Park, Maryland, to demonstrate the practical interface between PC-based image processing and hydrologic modeling. The Ringan GIS has not been offered commercially, but it is representative other systems relative to its application to hydrology. *Table 5.5* lists the major capabilities of the Ringan GIS.

The objective of the experiment was to use the ERDAS image processing system to define the land cover data plane for the 21 square mile Upper Anacostia River Basin located in the Maryland suburbs of Washington, D.C. This watershed was selected because it was one of the first to be modeled using Landsat-1 (Ragan and Jackson, 1975, "Hydrograph Synthesis Using Landsat Remote Sensing and the SCS Models," NASA X-913-76-161). Experience with ERDAS and IBM PC's would be especially interesting because the earlier effort required the use of General Electric's IMAGE 100 that rented for $240/clock hour and a UNIVAC 1108. The earlier effort required three hours of IMAGE 100 time with a specially trained operator and

TABLE 5.5: GIS CAPABILITIES WITH AN IBM MICROCOMPUTER

- Comprehensive GIS capabilities with an "off-the-shelf" PC;

- Develop and maintain multi-plane data bases for an entire area of jurisdiction such as a county or region;

- Define a sub area of interest such as a watershed from a digitizing table or by keyboard entry and:

    - Obtain color maps on a graphics CRT and symbolic maps on a printer that show the spatial distribution of:

        Land Use (existing or proposed)
        Soil Type
        Slope
        Zoning Categories
        Census Attributes
        Streets or Streams
        Specific Facilities

    - Produce statistical tables that tabulate the relative quantities of classes within each data plane;

    - Perform relational analyses that result in color crt and symbolic printer maps that show the locations of user-defined conditions among classes in several data planes;

    - Compute areas, lengths and distances;

    - Define parameters required for SCS hydrologic models and compute peak discharges and hydrographs for existing and user-defined watershed changes;

- Maintain communications with a supporting mini or mainframe computer to access mass storage devices or use faster computational capabilities; and

- Modify the model module of the overall system to accommodate different simulation packages.

the GIS was run on the UNIVAC 1108. The present effort was conducted entirely in a PC environment with two hours on the ERDAS and 10 minutes on the PC GIS. The staff running the ERDAS were civil engineers who had received two partial days of training during the system installation. They had received no formal training with the GIS other than "just working with it."

The ERDAS geometric corrections utility requires the input of ground control point coordinates. This can be done on the ERDAS system either through a digitizer or by keyboard entry. The present experiment used a digitizer interfaced to a totally independent PC. A PC utility was written in BASIC that allows the digitizer's x-y coordinates to be transformed to either Lat-Long or UTM and output to a floppy disk in a format that could be read by the ERDAS system. The ground control points and the boundary of the watershed on the four quad sheets were digitized, copied onto a floppy disk and taken to the ERDAS system.

In order to minimize the PC-AT running time required for the maximum likelihood classifier, ERDAS utilities were used to isolate a window from the 512x512 display. The classifier was run only on this 260 x 300 portion of the image. After the land cover classification was completed. The ERDAS utilities rotated the image, made the geometric corrections using the ground control points, conducted a supervised maximum likelihood classification, isolated the watershed from the rest of the image, resampled to provide a cell spacing of 5-second lat-long and then copied the results onto a floppy disk as an ASCII file.

The format, as required by the GIS, is a simple rectangular matrix with one character assigned as the land cover attribute for each cell. Each alphabetic character represents the land cover class for the cell location. Zeros are assigned, in this case, to the remaining cells surrounding the area of interest. In most instances the ERDAS is used to create floppy disks containing several complete quad sheets. The 5-second cell covers about 4.5 acres and is widely used by planning agencies. An ERDAS generated quad of this format stores as 8160 bytes. We also transfer quads with 236x300 pixels that store in 71.6 K bytes.

The Ringan GIS partitions its data bases into quad sheets to increase efficiency in the PC environment. The Ringan GIS runs the SCS models by overlying the land cover and soil data planes to define a curve number for each cell which is the averaged for all or a portion of the watershed. The slope data is used to compute the average watershed slope required for developing the hydrograph shape.

In the present experiment, a portion of the existing land cover is changed to show the ability of the GIS to examine the hydrologic consequences of alternative watershed development. Thus, a portion of a forested area is converted to a regional shopping center. *Figure 5.9* is a line printer map of the satellite derived existing land cover and *Figure 5.10* shows the land cover with the shopping center imposed. *Figure 5.11* shows the hydro-

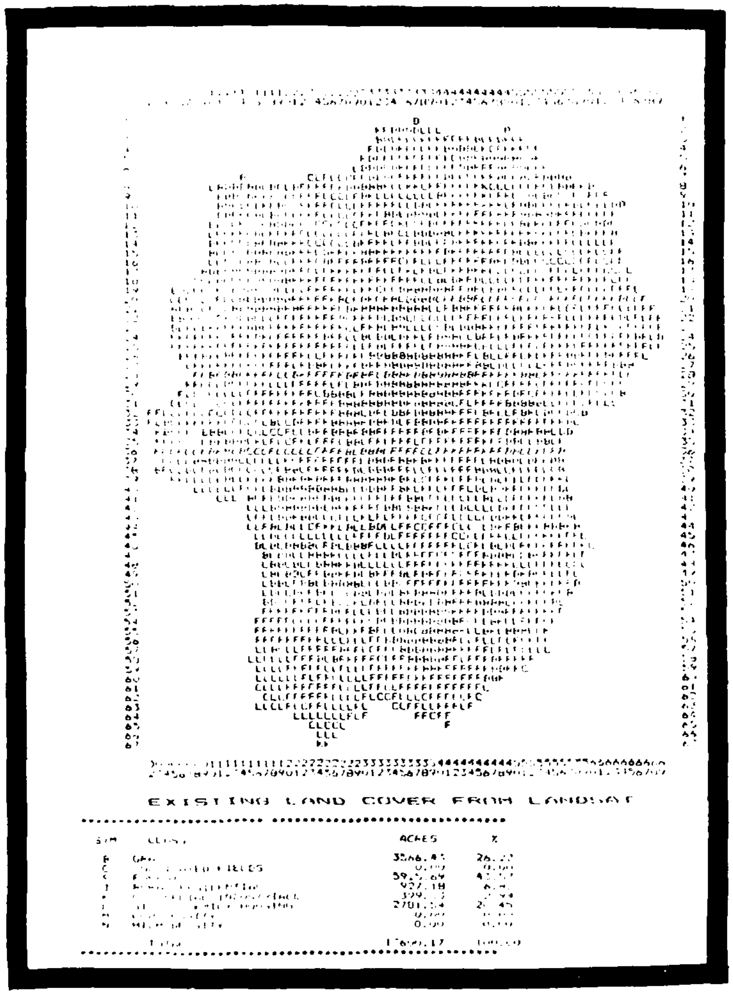

FIGURE 5.9. Line printer symbolic map and table of land cover distributions for *existing* land cover conditions of Anacostia watershed.

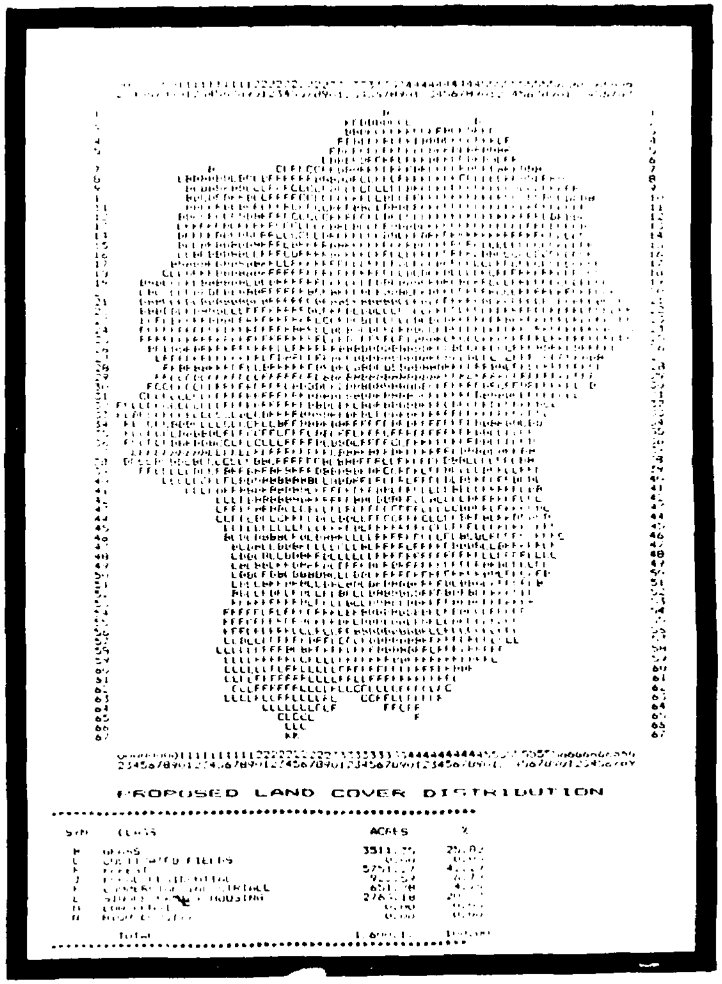

FIGURE 5.10. Line printer symbolic map and table of land cover distributions for proposed land cover conditions of Anacostia watershed.

AD-A195 809 REMOTE SENSING TECHNOLOGIES AND SPATIAL DATA APPLICATIONS(U) EARTH SATELLITE CORP CHEVY CHASE MD W G BROONER ET AL. DEC 87 DACW05-87-C-0012 2/2

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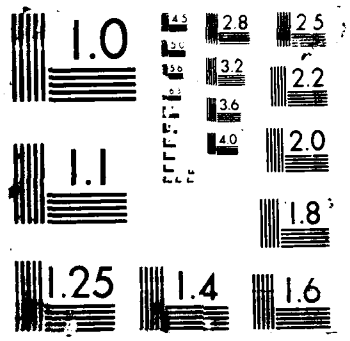
1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

****** SCS-TR-55 HYDROLOGIC ANALYSIS ******

**** RUNOFF HYDROGRAPH FROM TYPE II STORM DISTRIBUTION ****

PROJECT TITLE: IMPACT OF LAND COVER CHANGE
24 HOUR RAINFALL (INCHES) 4.80

AREA(ACRES)= 13600.17 SQ.MILES= 21.25027

QUANTITY	PRESENT	PROPOSED
CURVE NUMBER	65.76	66.[illegible]
PERCENT IMPERVIOUSNESS	10.27	11.79
AVERAGE PERCENT SLOPE	4.13	4.1
TIME OF CONCENTRATION (HOURS)	1.90	1.70
VOLUME OF RUNOFF (INCHES)	1.58	1.62
PEAK DISCHARGE	6816.[illegible]	7589.80

*** CHANGE IN RUNOFF VOLUME (INCHES) 0.04
*** CHANGE IN RUNOFF VOLUME (PERCENT) 2.81

*** CHANGE IN PEAK DISCHARGE (CFS) 781.01
*** CHANGE IN PEAK DISCHARGE (%) 11.42

TIME (HOURS)	DISCHARGE (CFS) PRESENT	PROPOSED
11.0	248.5	321.6
11.5	497.1	578.9
11.7	781.1	997.0
11.8	1065.1	1350.7
11.9	1349.2	1833.1
12.0	1739.7	2605.0
12.[illegible]	2272.3	3376.8
12.[illegible]	2840.3	4277.3
12.3	3372.9	5274.3
12.4	4047.5	6174.8
12.5	4722.0	6721.5
12.6	5396.6	7300.4
12.7	5858.2	7557.6
12.8	6213.2	7589.8
12.9	6532.8	7589.8
13.0	6816.8	7236.0
13.[illegible]	6745.8	6464.[illegible]
13.5	6248.7	4970.5
14.0	4580.0	3183.9
14.5	3301.9	2186.9
15.0	2414.3	1608.0
16.0	1455.7	1029.1
18.0	816.6	643.2
20.0	603.6	514.6

TABLE 5.6. Summary of watershed conditions, SCS model parameters and hydrograph discharge.

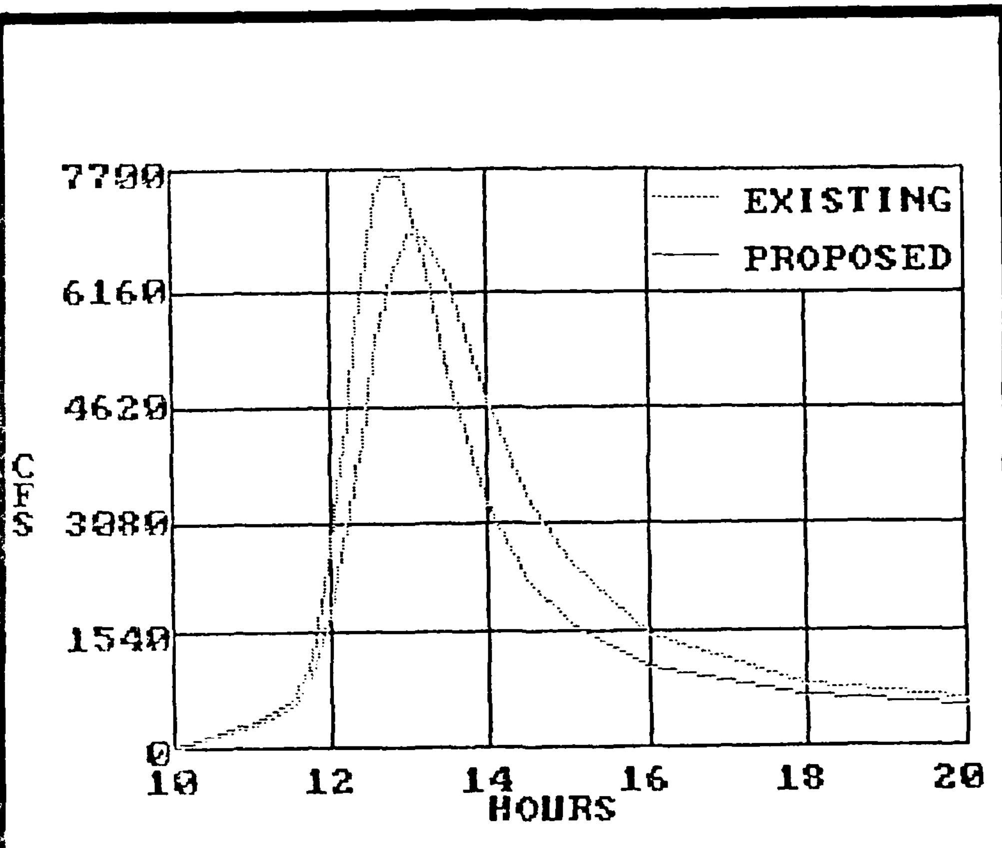

FIGURE 5.11. Line printer copy of color CRT display of hydrographs computed for existing and proposed land cover conditions.

graphs produced by a SCS-Type II 24-hour, 4.8 inch rainfall under existing and proposed land cover conditions. ***Table 5.6*** lists the hydrograph and SCS model parameters.

Figure 5.12 is another example of a GIS capability, relational analysis. The land cover, soil and slope data planes are overlaid in this approach to determine the location of all areas in the watershed that are either grass, cultivated or forested that are on either a C or D soil where the slope is greater than 10%.

This entire GIS analysis took less than 10 minutes with programs written in basic. The 512x512 window containing the watershed was isolated from the Landsat tape on a minicomputer and sent to the ERDAS for copying onto a 1.27 mb floppy disk. From that point on, all work was conducted in an IBM-PC environment by civil engineers whose training is primarily in hydrology rather than image processing. With its inventory of ERDAS systems and IBM PC's, the Corps of Engineers are in a position to fully implement the above and similar approaches.

A GIS package that runs on a PC does not appear to be available at more than a few Corps of Engineer facilities. At least some of the ERDAS units of the Corps were supplied with the GIS option. One approach would be for the Corps to add the ERDAS GIS to all existing units and move into PC-based Landsat modeling with a minimum start-up time. Unfortunately, the ERDAS GIS would be limited to PC's equipped with the ERDAS boards. The fully configured ERSI PC GIS will be available shortly (through either ESRI directly or through ERDAS) and should be seriously considered. There are no plans to market the Ringan GIS as a "software package." Because training and follow-up support are so critical. Ringan's plan is to distribute its GIS through a short course concept in which there is a fee charged for the training of each participant. At the end of the short course, the participants will be given a complete set of programs with no additional charges that are licensed to their organizations at the participants' duty locations.

6.0 *REAL TIME ESTIMATES OF PRECIPITATION AND SNOW COVER: AN EVALUATION OF HEC OPTIONS*

The Corps of Engineers through the Hydrologic Engineering Center (HEC) supports a wide range of hydrology-related activities. These include reservoir management and flood forecasting. The application of remote sensing tools and geographic information systems forms a future technology thrust for the Corps and HEC.

Remote sensing tools now available to hydrology extend beyond the well-demonstrated use of Landsat and SPOT to provide land cover information. Rather, any remote-sensing evaluation must extend to the meteorological satellites, i.e., GOES (geostationary) and NOAA (polar orbiter) and to the RADAP and NEXRAD meteorological radars.

Use of GOES and/or NOAA data to provide precipitation estimates, to map surface flood waters, and to map snow cover has been developed over the past two decades. Studies initiated over Africa by Barrett (1970), Follansbee (1973), Scofield and Oliver (1977) and over much of the world by Merritt et al. (1975) provide ample evidence that satellite estimates of rainfall are rather accurate for areas of about 25 by 25 miles.

The CROPCAST™ Agricultural Information System developed and operated by Earth Satellite Corporation, has used satellite rainfall estimates on a 25-mile scale for over 10 years. Accuracy estimates (Heitkemper et al., 1981) indicate RMS errors in 24-hour precipitation of 4 mm.

In 1986 a version of the CROPCAST System was developed and tested as a flash flood forecast system for Tulsa, Oklahoma. The Tulsa System used a 3 by 3 mile cell structure and combined radar (RADAP II) and ground measurements as its primary source of rainfall inputs; however, tests were conducted using GOES data to prepare rainfall estimates. Results of these tests support the concept that rainfall estimates can be made at a 3 by 3 mile cell level, (Merritt et al., 1986; Hlavka et al., 1986).

Snow cover has been mapped in both flat and mountainous river basins with satellite data from the Landsat, NOAA (AVHRR) and GOES satellites for more than two decades. Results of this work show conclusively that although snow area can be mapped, very little can be determined about snow depth and nothing can be said about snow water equivalent.

The problem of snow depth and water equivalent has been taken on by CROPCAST in addressing the winter grain kill problem. Using a budgeting procedure which continuously monitors the conditions occurring during snow fall and which inputs only a measurement of reported liquid water equivalent (in the USSR) the CROPCAST snow budget estimates snow depth and snow water equivalent. This information is used to (a) assess the insulating potential of snow cover under very cold conditions and (b) provide an estimate of the water that will enter the soil during spring melt in order to initialize the CROPCAST soil water budget.

Although there is no question that satellite sensors from both earth resources and meteorological-type satellites can provide useful data for hydrology, satellite data should be considered in the context of the various other data sources, i.e., radar and ground observations as well as in the context of models such as the CROPCAST snow budget model. The source and context of hydrologic input data also needs to be evaluated in terms of the precision of the hydrologic models using the input data.

The following sections outline two sources for satellite-derived rainfall and snow-cover information and examine costs for each source in terms of a Corps' operational need.

6.1 *Satellite Rainfall Estimates - Sources and Cost Estimates*

There are essentially two potential active sources, today, for satellite-derived rainfall estimates in the U.S. These sources are:

1. NOAA - via the Integrated Flash Flood Analysis (IFFA) Program in the World Weather Building, Camp Spring, Maryland. Contact Dr. R. Scofield (301) 763-8282.

2. Earth Satellite Corporation, CROPCAST, 7222 47th Street, Chevy Chase, Maryland. Contact Mr. Earl S. Merritt (301) 951-0104.

A potential alternative would be for the Corps to acquire the skills, hardware and software for them to develop estimates themselves for all operational needs.

6.1.1 *NOAA - R. Scofield*

Visits with Dr. Scofield to review the potential for NOAA to serve the Corps' needs produced the following information:

a. If the Corps wants a full time precipitation support facility the costs would be based on development of a separate dedicated unit at the World Weather Building to support Corps needs. Estimated costs for this option would be:

Start-Up Costs

Interactive hardware	$150,000
Interactive software	50,000
Total	$200,000

Continuing Costs

Five (5) Senior Meteorologists
Two (2) Hardware Contractors
One (1) Software Contractor

Total	$500,000/Year

This estimate does not include any cost for digital satellite data (presumably it could supplied at low cost under inter-government agreements).

If the Corps does not have a continuing need but rather has limited experimental requirements it may be possible for the local weather office to arrange support, but such support would be limited and would often depend on the goodwill developed between the Corps and the local NWS Meteorologist-in-Charge.

In either case NOAA support with satellite data would be based on the IFFA System and would therefore provide a county level estimate. Some large counties can be subdivided. There is no current plan in NOAA to provide grid cell precipitation data.

6.1.2 *CROPCAST™ - E. Merritt*

The CROPCAST System is in full-time worldwide operation. Precipitation derived from satellites enters the system every six hours in a 48 km x 48 km cell structure. CROPCAST System algorithms merge satellite-derived estimates with available ground reports using an objective analysis procedure. The integrated rainfall estimate has a RMS error of about 3 mm/day.[6/] Thus, the merger procedure reduces the RMS error by nearly 1 mm/day.

The cost to receive CROPCAST precipitation estimates developed from merger of radar (digital summary), ground service A/C reports and satellites at six-hour and 24-hour intervals on a 36 by

2

6/ Tests were conducted of EarthSat's precipitation estimates using 31 rain event cases chosen from events over the central and eastern United States in 1978 and 1979. Evaluations of satellite alone, ground station alone and CROPCAST combined system errors were made. The results are shown in *Table 6.1* and *Figure 6.1* as reproduced from the Final Report under Contract NA-80-SAC-00747 with U.S. Department of Commerce, NOAA/NESS, August 15, 1981. The report was authored by L. Heitkemper, E. Merritt, D. Hlavka and K. Marcus of EarthSat's CROPCAST™ Group. The errors presented in the table and figure are for 48 km cells and 24-hour time intervals. The "truth" used was average rainfall derived from climatological reports not available to the original analysis. An analysis which includes radar alone or covers areas smaller than 48 km has not yet been performed.

TABLE 6.1: IMPROVED RAINFALL STATISTICS

	Avg. Error (mm)	RMSE (mm)	% Cases (3mm)	% Cases (7mm)
System Rainfall Algorithm	4.52	7.90	77.1	88.1
Satellite Alone Estimate	5.23	9.05	73.1	85.8
Station Interpolation	4.48	8.43	77.5	86.6
Closest Station	4.96	9.62	79.4	85.9
Improved Satellite Alone	4.42	7.95	78.3	88.7
Improved System	3.84	7.40	82.2	91.5

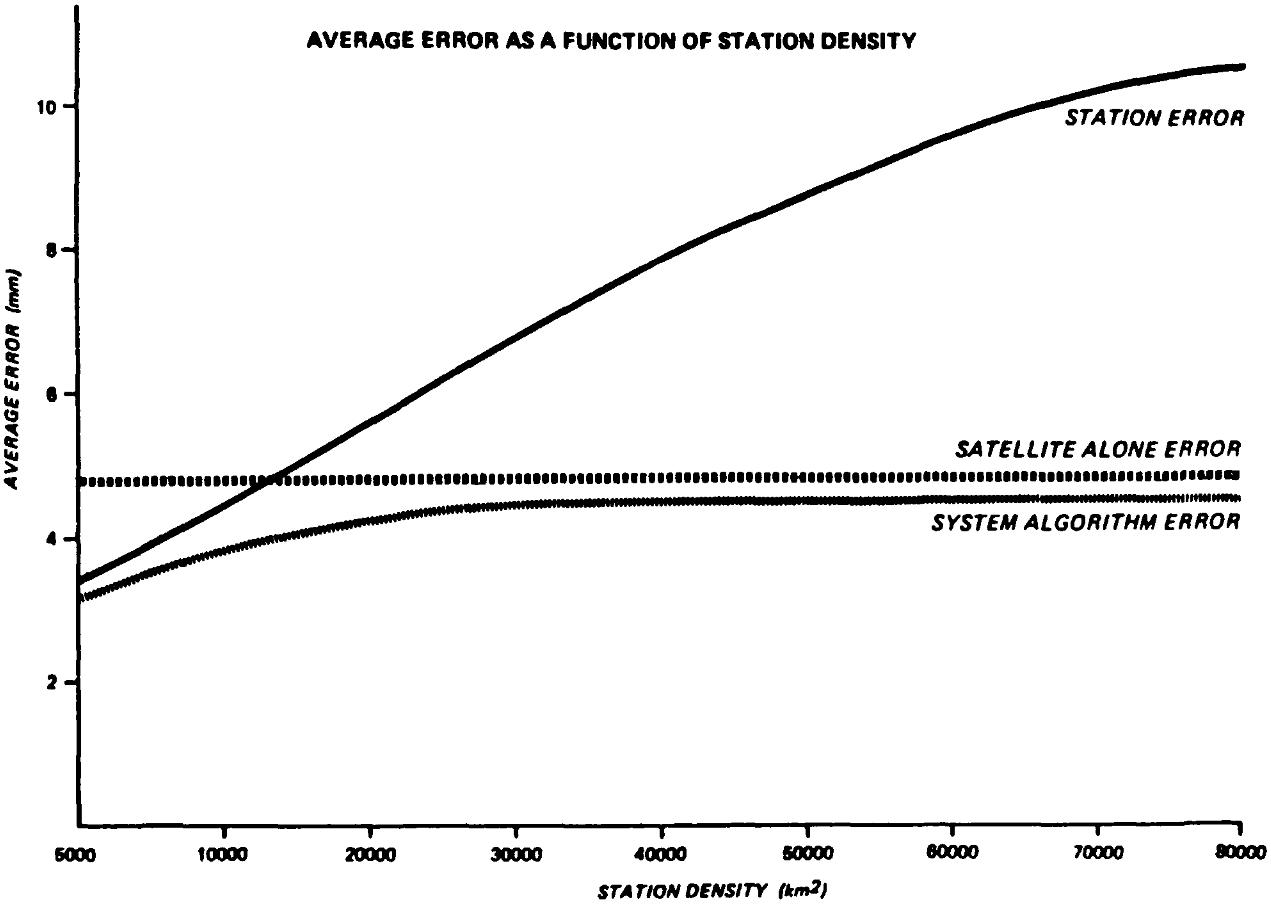

FIGURE 6.1 : ERROR ANALYSIS AS A FUNCTION OF STATION DENSITY

36 km cell basis would be approximately $4,000/month. Minimum performance periods could be negotiable but would be expected to be three months.

If the Corps wished to have CROPCAST improve the cell resolution of the data or increase the frequency of delivery additional labor would be required, estimated as:

One (1) full time Meteorologist	$ 75,000
One (1) Meteorologist Tech	25,000
	$100,000/Year

This option would provide the Corps with a dedicated team and outputs at about a 18 km by 18 km resolution with precipitation estimates delivered at three-hour intervals. This option would also provide forecast support for Corps problems 12-16 hours per day.

6.1.3 *Corps - In-House Facility*

Development of an in-house capability for Corps satellite precipitation support can take two primary approaches. The basic output of the two approaches is similar.

a. Duplicate the NOAA IFFA System at a Corps facility, or
b. Duplicate the CROPCAST System at a Corps facility.

In addition to the options listed previously it would be possible for HEC to develop a capability to use the GIS together with satellite, radar and ground report in a qualitative form to improve rainfall assessments. However, it appears that the effort could benefit from some of the data handling algorithms developed by CROPCAST. This approach, would add a relatively small amount of cost, which would be offset by reducing the manpower needed to reinvent the procedures. The CROPCAST system is a relatively straightforward GIS based process that uses polygon or run length data entry, grid-cell data storage and map-based output.

6.1.3.1 *Duplication of NOAA Facilities*

The estimated cost to duplicate the NOAA IFFA system is very similar to NOAA's proposal to meet Corps needs, i.e.,

Start-Up

Interactive Hardware	$150,000
Interactive Software	50,000
NOAA Training Support	TBD*
Total	$200,000*

Recurring Costs

Five (5) Meteorologists	
Two (2) Hardware Contractors	
One (1) Software Contractor	
Total Estimate	$500,000/Year

Family of Services

Domestic Line	2,000/Year
Public Services	2,500/Year
Satellite Data Line	50,000/Year
Total Estimate Recurring	$554,500/Year
Non Recurring	200,000
First Year Costs	$754,500

6.1.3.2 *Duplication of CROPCAST Facilities*

Start-Up

Interactive Hardware[7]	$25,000
Interactive Software[8]	50,000
CROPCAST Training[9]	7,000
Total	$82,000

Recurring Costs

Two (2) or three (3) Meteorologists	$150,000
1/2 Hardware support contract staff	50,000
	$200,000/Year

2

7/ Interactive Hardware System PC/AT, EGA, Digitizer plus Image Capture Board

8/ CROPCAST System Purchase

9/ Fourteen (14) days @ $500/day (Estimated 3 person/weeks on-site plus expenses.

Family of Services

- Domestic Line	$ 2,000/Year
- Public Service	2,500/Year

GOES Tap

- Harware Lease	$ 10,200/Year
- Expendables	incl.
Total	$296,700/Year

The key differences between the NOAA IFFA System and the CROPCAST System design are in the hardware and software. CROPCAST's hardware builds on its use of hard copy image data received on the GOES Tap line whereas NOAA's System is tied to the digital data stream from GOES. This allows CROPCAST to use an inexpensive PC-based system while NOAA must use a much more expensive, specially designed system. CROPCAST software is designed to merge satellite, ground reports and digital polar summaries and then to provide an integrated precipitation value whereas the NOAA system provides a satellite only output.

6.1.4 *Summary of Satellite Precipitation Options*

The options available to the Corps for satellite-derived precipitation estimates range from setting up a dedicated facility at NOAA, to purchasing data from EarthSat CROPCAST, to establishing an in-house capability. The costs for these options vary widely. On a cost basis, CROPCAST option is highly cost effective. From a control of data source basis, an in-house system would probably be preferred; obviously, the decision must also include policy and administrative considerations.

6.2 *Satellite Snow Area Data and Related Activities*

There are essentially two potentially active sources for snow area information from satellites in the U.S. These sources are:

a. NOAA - NWS - Federal Building, Room 1728, 601 East 12th Street, Kansas City, Missouri, Milam Allen (816) 374-3427, FAX 758-3217.

b. Earth Satellite Corporation - CROPCAST™, 7222 47th Street, Chevy Chase, Maryland, joined with Satellite Hydrology Inc. at 7222 47th Street, Chevy Chase, Maryland. Contacts Earl S. Merritt or Donald Wiesnet (301) 951-0104.

6.2.1 *Corps In-House Facility*

Development of an in-house capability for Corps satellite snow-covered area support can have two approaches. The basic output of the two approaches is similar.

a. Duplicate the NOAA System at a Corps facility, or
b. Duplicate the CROPCAST System at a Corps facililty.

6.2.2 *Duplication of the NOAA Facilities*

The estimated cost of duplicating the NOAA snow cover mapping system is as follows:

Start Up:

Interactive Hardware	$150,000
Interactive Software	50,000
NOAA Training Support	(incl)
Total	$200,000

Recurring Costs:

2 Satellite Hydrologists	
1 Computer Programmer/Analyst	
1 Hardware Contractor	
1 Software Contractor	
Total	$400,000/yr

Family of Services:

Domestic Line	$ 2,000/yr	
Public Services	2,500/yr	
Satellite Data Line		50,000/yr

Total Estimate Recurring:	454,500
Total Estimate Nonrecurring:	200,000
First Year Costs:	$654,500

6.2.3 *Duplication of the CROPCAST Facilities*

Start Up:

Interactive Hardware	$ 25,000
Interactive Software	50,000
CROPCAST Training	7,000
	$ 82,000

Recurring Costs:

2 or 3 Meteorologists	$150,000
1/2 Hardware Support	50,000
	$200,000/yr

Family of Services:

Domestic Line	$ 2,000/yr
Public Services:	2,500/yr

GOES Tap.

Hardware Lease	$ 10,200/yr
Expendables	(incl)
	$296,700

The key differences between the NOAA IFFA System and the CROPCAST System design are discussed in Sections 6.1.

6.3 *A Dual System for both Precipitation Estimation and Snow Cover Maps*

The estimated costs for snow cover mapping and precipitation estimating are similar because of similar hardware, software, and training requirements, and similar services and personnel costs. It would be highly cost effective to establish a dual system that could accomplish both purposes. *Table 6.2* compares these costs.

TABLE 6.2: COST COMPARISON OF PRECIPITATION ESTIMATION, SNOW COVER MAP, AND A COMBINED SYSTEM FOR CORPS FACILITY

	Precip. Est.		*Snowcover Map*		*Dual System*	
	NOAA	*CROPCAST*	*NOAA*	*CROPCAST*	*NOAA*	*CROPCAST*
Start Up						
Interactive Hardware	150K	25K	150K	25K	150K	25K
Interactive Software	50K	50K	50K	50K	50K	50K
Training Support	Incl.	7K	Incl.	7K	Incl.	7K
	200K	77K	200K	77K	200K	77K
Running Costs						
Personnel	500K	200K	400K	200K	700K	300K
Family of Services						
Domestic Line	2K	2K	2K	2K	2K	2K
Public Services	2.5K	2.5K	2.5K	2.5K	2.5K	2.5K
Satellite Data Line	50K	10.2K	50K	10.2K	50.K	10.2K
	54.5K	14.7K	54.5K	14.7K	54.5K	19.7K
Total Estimated Recurring	$554.5K	214.7K	454.5K	214.7K	754.5K	214.7K
Total 1st Year Costs	754.5K	296.7K	654.5K	296.7K	954.5K	296.7K

A dual system for both precipitation estimation and snow cover mapping is another alternative. Duplication of a CROPCAST system for dual purposes would cost significantly less the first year than duplicating the NOAA system. Recurring annual costs would also be less than those of the NOAA system.

6.4 *CROPCAST Snow Budget*

The CROPCAST System generates snow depth and water equivalent information throughout the winter season. Calculations are made at the Service A and Service C reporting stations. Satellite observations of snow area are periodically compared with the model output to assess model accuracy. While these data have not been used for hydrology it does appear that such data could be overlayed on the satellite-derived snow area coverage to provide an estimate of variations in depth and snow water equivalent. The estimated cost of providing the CROPCAST output to the Corps would be about $1,000 per month for all locations in the U.S.

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APPENDIX A

REMOTE SENSING BY THE CORPS OF ENGINEERS RELEVANT TO HEC ACTIVITIES PROGRAM

The U.S. Army Corps of Engineers became actively involved in applying remote-sensing technology for hydrologic engineering and planning activities in the early 1970's. The results of initial studies were reported at the First Remote Sensing Symposium of the Corps held at the NASA Manned Spacecraft Center at Houston in 1975, but the proceedings were not published (Jarman, personal communication). In 1975 most of the presentations were by hardware developers or principal investigators who described remote-sensing theory, instrument design and data processing.

The Second Corps of Engineers Symposium (USACE, 1979) was held at Reston, Virginia, and a variety of presentations were made on data collection, sensors and applications directly or indirectly relevant to the Hydrologic Engineering Center's research and technical assistance functions. *Table A-1* is a listing of applications, platforms, and sensors described in papers that should be of direct interest to HEC.

The role of remote sensing by the Corps of Engineers was succinctly and effectively stated by the Deputy Chief of Engineers, R.M. Wells (in USACE, 1983, p. 173). He stated, "Remote sensing's role in the future is as a data collector--a way of collecting larger amounts of data, reducing labor intensive efforts, and providing more timely data more quickly." The responsibilities of the Hydrologic Engineering Center relating to remote sensing could be similarly stated, but limited to application's within its functions of research, technical assistance and planning.

By 1981, remote-sensing technology relevant to applied hydrologic engineering, planning and research by various Corps of Engineer offices had become both more sophisticated and more widely used. Significant advancements were made using advanced data processing systems and improved analysis capabilities. At the Third Remote Sensing Symposium held at Nashville, Tennessee (USACE, 1981), Moore (p. 114) reported on processing capabilities for hydrologic information systems. He suggested a six-step approach to data processing consisting of data selection and preparation, parameter evaluation, areal stratification, data merging and integration, model derivation and testing and use of operational models. Bartolucci and Davis (p. 131) reported that Landsat data in digital format together with numerical, computer-aided analytical techniques can provide more information at a higher level of mapping detail than can be achieved using photointerpretation techniques. Algazi et al. (p. 145) determined land-use classification by computer processing of Landsat data and applied the resultant information content to hydrologic planning models.

Table A-2 is a listing of applications, platforms and sensors applicable to Hydrologic Engineering Center's planning, research and technical assistance functions as reported at the Third Symposium.

TABLE A-1: USACE REMOTE SENSING ACTIVITIES IN HYDROLOGIC ENGINEERING AND PLANNING THROUGH 1979

Application	Platform	Sensor	Author(s)	Page[1/]
Modeling basin geometry	Aircraft	Laser profilometer Radar altimeter	Collins and Krabill,	63
Measure water depth	Aircraft	Pulse laser	Enabit, et al.	70
Geologic analysis of demsites	Aircraft	SLAR	Galster	79
Land cover classification, comparison	Aircraft vs Landsat	Camera vs MSS	Holmes and Dodge	83
Stream bank erosion control, planning and development	Aircraft	Camera	Soyke and Rakus	171
Stage-area relationships	Landsat	MSS	Hudson and Struve	193
Land clearing for flood control project analysis	Aircraft and Landsat	Camera and MSS	Wilcox and Struve	201
Dam safety	Landsat	MSS	Dumas and Blystra	219
Land use parameters in hydrologic models	Landsat	MSS	Feldman and Cermak	225
Snow Cover mapping	Landsat	MSS	Merry et al.	229
Damsite excavation volumes	Aircraft	Stereo camera	Dodge and Holmes	277
River basin environmental analysis	Landsat	MSS	Long et al.	279
River turbidity plumes caused by dredging	Aircraft	Multi band cameras	Sherz et al.	281
Interdisciplinary image analysis in planning	Air and spacecraft	All	Frost	309

Application	Platform	Sensor	Author(s)	Page1/
Rainfall estimation	Satellites	IR radiometers	Whitney and Herman	313
Earth dam and dike site selection	Aircraft Landsat	Camera MSS	McKim and Merry	327
Wetland mapping	Landsat	MSS	Rundquist and Gilbert	329
Wetland Change detection	Landsat	MSS	NYC and Brooks	333
Aquatic plant mapping	Aircraft	Camera	Link and Long	345
Crop damage due to flooding	Aircraft	Camera	Soyke	353

1/ in USACE, 1979, Proc. Second Remote Sensing Symposium: U.S.A. Engineer Topographic Laboratories. Ft. Belvoir, VA. 22060.

TABLE A-2: USACE REMOTE SENSING ACTIVITIES IN HYDROLOGIC ENGINEERING AND PLANNING THROUGH 1981

Application	Platform	Sensor	Author(s)	Page[2/]
Spatial data management in water resources planning	Any	Any	Davis	8
Remote-sensing based hydrologic modeling	Landsat	MSS	Ragan	11
Erosion Control	Aircraft	Cameras	Adams	32
Operation of flood-control structures	GOES	DCP's	Buckeley	34
Land-use classification in hydrologic modeling	Landsat	MSS	Feldman and Cermak	42
Suspended sediment modeling	Landsat	MSS	Hill and Harlow	46
Hydrologic data collection	GOES	DCP's	Shope	48
Environmental data collection for water management and control	GOES	DCP's	Sharp	68
Profiling and bathymetry	Aircraft	Laser	Link and Collins	74
Soil moisture determination for hydrologic forecasting	Aircraft	Microwave radiometers	Jackson	90
Coastal engineering	Landsat	MSS, RBV	Lichy	93
Terrain mapping	Aircraft	Laser	Krabill et al.	99
Shoreline mapping	Aircraft	Laser	Boone	100
Flood related crop damage	Aircraft	Camera	Mroczynski et al.	105

Application	Platform	Sensor	Author(s)	Page[2/]
Calculations of flood damage of structures	Aircraft Landsat	Cameras, MSS, TM	Merry	112
Snow cover mapping	Landsat	MSS	Merry	153
Regulating wetland activities	Landsat	MSS	Stoll and Hughes	157
Benefit-cost analysis in flood control	Landsat	MSS	LaGarde et al.	158
Inventory of non-federal dams	Landsat	MSS	McKim et al.	169
Floodplain management	Landsat	MSS	Gervin et al.	186

2/ *in* USACE, 1981, Proc. Third Remote Sensing Symposium: U.S.A.C.E. Water Resources Support Center, Ft. Belvoir, VA 22060

The Fourth Remote Sensing Symposium was held at Reston, Virginia (USACE, 1983) and further advances relevant to hydrologic engineering, planning and research were reported. Operational uses of remote sensing from various Corps Divisions, Districts and Laboratories were rapidly expanding. Remote sensing in the Corps of Engineers was in transition from experiment to beneficiary usage in operational systems (Jarman, *in* USACE, 1983, p. 1). Many of the papers were given by the user community and the presentations were of greater depth and scope than ever before. Progress could be measured by advances in the Corp's capability to undertake broad operational missions. Substantial progress was made in data handling, processing and distribution.

Some user missions, especially in the field of hydrology require fully processed satellite data within 24 to 48 hours after observation; much faster than the Corps had been able to provide it. An important step in overcoming this deficiency was made by the implementation of the Landsat Emergency Access and Products (LEAP) Program by the Corps of Engineers.

Of special significance to the hydrologic user community within the Corps of Engineers was the significant advance in data distribution during the early 1980's. NASA launched the first tracking and data relay satellite (TDRS) to collect and relay data transmissions from orbiting platforms in real time, eliminating complete reliance on tape recorders for on-board data storage. The increasing availability and decreasing costs of DOMSAT communication links made them more efficient and cost effective as primary channels for distributing remote sensing data to users.

Jarman (USACE, 1983, p. 2), however, pointed out the need for immediate and intense concentration in the development of user models if the potential operational remote sensing is to be fulfilled. "A user model," he stated, "is usually defined as the algorithm or procedure that translates remote-sensing data into a form directly usable by resource managers for decision-making." Hydrologists had already taken the first step by using remote sensing to model and predict runoff. He cited the five-day weather forecast as another example in which satellite data are used in model.

Table A-3 lists presentations made at the Fourth Remote Sensing Symposium relevant to the Hydrologic Engineering Center's planning, research and technical assistance functions.

The Corps of Engineers has had a long record in disaster response and anticipates future added duties (Dawson, *in* USACE, 1983, p. 25). As a result of the transfer of responsibilities under Executive Order 11490 for water management in national emergencies from the Department of the Interior to the Corps of Engineers, the Corps will play an even larger role in water-resource emergencies and mobilization support activities. This responsibility will entail increased effort to plan for both drought and flood emergencies, including drought contingency planning, flood warning and preparedness planning.

Remote sensing data will play an increasingly important role to sustain and improve the Corp's quick response capabilities in disaster

TABLE A-3: USACE REMOTE SENSING ACTIVITIES IN HYDROLOGIC ENGINEERING AND PLANNING REPORTED AT THE FOURTH SYMPOSIUM

Application	Platform	Sensor	Author(s)	Page[3/]
GIS applied to Corps planning in flood control	--	--	Davis and Ford	29
Spatial analysis methodology (SAM) for flood damage assessments	Aircraft Landsat	Aircraft Thematic Mapper (simulated)	Edwardo	59
GIS to mitigate conflict and enviromental damage	Landsat	MSS	Gay	75
Water control	GOES	DCP's	Coombs	95
Detection of submerged aquatic vegetation	Landsat	TM	Ackleson and Klemas	197
Tracing coastal waste disposal plumes	Landsat	MSS	Fedosh	223
Providing hydrologic data in real time	GOES	DCP's	Shope and Paulson	231
Detection of ground-water indicators	Landsat	MSS	Crabtree	259
GIS watershed model	Landsat	MSS	Groves et al.	275
Coastal ocean dynamics	Land surface	Radar	Hubertz	277
Management of suspended sediments	Landsat	MSS and TM	Ritchie et al.	289
Management planning for lake restoration	Landsat GOES	MSS and TM DCP's	Schiebe	247
Flood damage assessments	Aircraft	Cameras	Newberry	323
Snow pack measurements for water supply forecasting	Aircraft	Gamma radiation spectrometer	Gauthier et al.	341

Application	Platform	Sensor	Author(s)	Page[3/]
Emergency access of data for disaster response	Landsat	MSS	Pepe and Lichy	343
Land cover classification for hydrologic modeling	Landsat	TM and MSS	Cermak et al.	347
Spatial soil moisture data for hydrologic modeling	Aircraft	Gamma ray detector	McKim and Pangburn	355
Satellite resolution data for flood damage calculations	Aircraft	MSS and TM simulations	Merry	385
Wetlands classifications	Landsat Aircraft	TM and TM simulations	Mulligan et al.	399
Suburban watershed land cover classification for hydrologic modeling	Landsat Aircraft	TM and TM simulations	Gervin et al.	405
Floodplain cover mapping for flood damage-potential models	Landsat Aircraft	TM and TM simulations	Kerber et al.	421
Integrating Landsat data into grid-cell data banks	Landsat	MSS	Wanielista et al.	431
Real-time data collection of monitoring and modeling	GOES	DCP's	Nanda	433
Detection of suspended sediment impact	Landsat	MSS	Bragg and Sharp	439
Flood mapping for near real time operations planning	Landsat	MSS	Bragg and Sharp	439

3/ USACE, 1983, Fourth Remote Sensing Symposium: U.S.A.C.E., Water Resources Support Center, Ft. Belvoir, VA 22060

response. The Corps of Engineers is working with the Federal Emergency Management Agency in developing an operational procedure to coordinate emergency acquisition of satellite and aircraft remote sensing for a quick response during national disasters. Development of operational procedures--especially when flood or storm emergencies are involved--fall within the purview of the Hydrologic Engineering Center's research and technical assistance mandates.

By the time of the Fifth Corps of Engineers Remote Sensing Symposium, held at Ann arbor, Michigan in October 1985, numerous District and Division offices had begun to apply remote sensing technology operationally. Indeed the symposium was organized by the District and Division offices many of the presentations were made by the field offices using state-of-the-art technology (Lichy, 1985).

At the Fifth Symposium, the Chief of Engineers went on record with his belief "that it is time to increase our use of remote sensing technology to augment our data acquisition requirements in support of our engineering and construction programs; just as we have had it for our planning and operations activities."

Table A-4 lists the various applications made of the technology by the laboratories and field offices that were reported during the fifth symposium. This listing suggests areas of research and technical assistance in hydrologic engineering that might be addressed by HEC for purposes of advancing the state-of-the-art.

The Hydrologic Engineering Center should significantly increase its participation in Corps of Engineers and other symposia in the fields of remote sensing and applied engineering to demonstrate its considerable expertise and capabilities in research and technical assistance for the District and Division offices. Co-authorship of papers and presentation's by HEC and field scientists would be helpful in gaining recognition and funding for HEC in future activities required for advancing the state-of-the-art. Indeed HEC should give serious consideration to hosting and organizing Corps Remote Sensing Symposia in the future.

TABLE A-4: USACE REMOTE SENSING ACTIVITIES IN HYDROLOGIC ENGINEERING THROUGH 1985

Application	Platform	Sensor	Author(s)	Page[4/]
River mouth sedimentation	Landsat Metsat Space Shuttle	MSS AVHRR Camera	Soileau et al.	23
Hydrodynamic modeling of Great Lakes connecting channels	GOES	DCP's	Thomas and Wilshaw	34
Master planning for lake resources management	(SPOT simulation) Aircraft	Camera Multispectral sensor simulation	Eduardo et al.	46
Evaluating water retention sites	Landsat	TM	Green and Merry	57
Monitoring river ice	Aircraft	Video camera	Gatto et al.	60
Reservoir regulation	GOES	DCP	Gauthier and Weiser	92
Wetland loss and regeneration	Aircraft Landsat	Camera MSS, TM	Lyon et al.	106
Assessment of flash flood potential	Land based	Nex rad	Walton et al.	123
River Valley profiling	Aircraft	Laser profiler	Stoll	149
Deep water dredge material disposal	Surface based	UHF electroni positioning system	Simonelli and Bergen	182
Grid cell land cover data file	Landsat	MSS	Goldman	185
Snow cover mapping	GOES	VISSR	Allen and Mosher	195

Application	Platform	Sensor	Author(s)	Page[4/]
Runoff volume in hydrologic models	Landsat	MSS	Drungil	205
Near real-time assessment of flood events	Landsat	MSS	Soileau et al.	233
Emergency flood monitoring	NOAA	AVHRR	Stoll and Svejkovsky	248
Land-cover mapping as inputs to hydrological models	Landsat	TM	Gervin et al.	249
Floodplain land cover for flood control management	Landsat	MSS and TM	Kerber et al.	262
Snow water equivalent for flood warning	Aircraft	Gamma radiation spectrometer	Carrol and Marshall	287
Resource inventory data for river channel and leveed floodplain	Aircraft	Camera (infrared file)	Cobb and Williamson	450
Change detection for flood damage assessment	Landsat	MSS and TM	Edward et al.	478
Hydromet data for forecasting and regulating water levels	NOAA and TIROS	AVHRR and TOVS (Tiros operational sounder)	Gauthier	535
Personal computer workstation for GIS and hydrologic modeling	--	--	Ragan	537
Real time observations of flooding and sediment deposition	NOAA, GOES	AVHRR; VISSR	Parmenter-Holt	555

4/ USACE, 1985, Remote Sensing Applications for Water Resources Management: Proc. USACE Fifth Remote Sensing Symposium, Water Resources Support Center, Ft. Belvoir, VA 22060

APPENDIX B

OVERVIEW OF NEW AND NEWLY OPERATIONAL SATELLITE SENSORS

B.1 *Introduction*

In March 1972, a paper by Brooner and Nichols began with the following sentences -- ones which are equally applicable in 1987:

> *"In the past decade the field of remote sensing has produced increasingly sophisticated and useful tools to be applied to environmental programs and problems. Among the relatively few who have observed or participated in this development, remote sensing has effectively and efficiently demonstrated the ability to meaningfully record a multitude of phenomena in our environment. Many recently demonstrated applications have become operational."* (Brooner and Nichols, 1972)

Approximately four months later, NASA launched into orbit the first Landsat type satellite. Success of Landsat-1, an experimental program, has been followed by launches of four more Landsats, program transfer to operational status administered by NOAA (1983) and commercialization by EOSAT (1985), and launch of the first non-U.S. (France) commercial remote sensing satellite, SPOT-1, in 1986, and the Japanese MOS-1 satellite in 1987.

In addition, a series of geostationary environmental satellites operated by the U.S. (GOES), France (Meteosat) and Japan (GMS) provide real-time meteorological observations worldwide, complimented by a series of polar-orbiting environmental satellites operated by the U.S. (NOAA AVHRR) and Soviet Union (Meteor).

Additional earth resources and environmental satellites are planned into the next decade. While the U.S. dominated the satellite remote sensing industry for 14 years, it is today a truly international initiative. International remote sensing systems reflect the growth and potential of a global industry, and open the door to interntional cooperation and better management of the earth's resources.

Numerous references have documented the characteristics of each satellite's sensors and performance as well as developmental and operational applications of the remotely sensed data. The following discussion, along with attached tables and figures, provides comparisons of the main features, including orbits and sensors, for the series of Landsat, SPOT, MOS and NOAA satellites (*Table B.1*).

TABLE B.1: SELECTED OPERATIONAL EARTH RESOURCES SATELLITES

Inactive Platform		*Country*	*Sensor*
Landsat-1	1972-1978	USA	79 meter MSS
Landsat-2	1975-1982	USA	79 meter MSS
Landsat-3	1978-1983	USA	79 meter MSS 38 meter RBV
Active as of December 1987			
Landsat-4	1982-	USA	79 meter MSS 30 meter TM
Landsat-5	1984-	USA	79 meter MSS 30 meter RBV
SPOT-1	1986-	France	20 meter MS 10 meter Pan
MOS-1	1987-	Japan	0.9 km/2.7 km VTIR 50 meter MESSR 31 km MSR
NOAA-8		USA	AVHRR
NOAA-9		USA	AVHRR
GOES		USA	VAS VISSR

The Landsat and SPOT series of satellites are both designed for regular, intermediate-to-broad area coverage of the earth's surface, providing medium-to-low resolution multispectral data at low cost per square kilometer. Significant comparative differences, however, exist among the principal sensors, e.g., Landsat's Multispectral Scanner (MSS) and Thematic Mapper (TM) and SPOT's multispectral and panchromatic operation modes, the MOS-1 multispectral radiometer (MESSR), and the NOAA AVHRR and GOES systems (*Table B.2*).

TABLE B.2: COMPARISONS OF SELECTED SATELLITE REMOTE SENSING SYSTEMS

	Landsat Multispectral Scanner (MSS)	Landsat Thematic Mapper (TM)	SPOT Multispectral (MS)	SPOT Panchrometic (Pan)	MOS-1 (MESSR)	NOAA, 8, 9 Advanced Very High Resolution Radiometer (AVHRR)	GOES (VISSR)
Spectral Bands (Micrometers)		0.45-0.52					
	0.5-0.6	0.52-0.60	0.51-0.59	0.51-0.73	0.51-0.59		
	0.6-0.7	0.63-0.74	0.61-0.68		0.61-0.70	0.58-0.68	0.54-0.70
	0.7-0.8	0.76-0.90	0.79-0.89		0.72-0.80		
	0.8-1.1				0.80-1.10	0.72-1.10	
		1.55-1.75					
		2.08-2.35					
						3.55-3.93	
		10.50-12.50				10.50-12.50	10.50-12.60
Area Coverage Per Image (Square Kilometers) * Width of Swath	34,225 *185	31,450 *185	3600 *60	3600 *60	10,000 *100	*2940 (NOAA-8) *2600 (NOAA-9)	
Instantaneous Field of View (Resolution, meters)	80	30 120 (Thermal)	20	10	50	1100 (NOAA-8) 500 (NOAA-9 visible) 1000 (NOAA-9 Thermal)	1100/4000
Repeat Cycle	16 days	16 days	5/20 days	5/20 days	17 days	12 hours	20 min,/1 min.
Turnaround (time between acquisition and delivery)	4 weeks	4 weeks	4 weeks	4 weeks		2 weeks	Real time
Data Cost per sq. km (Digital Data)	$0.020	$0.105 (full scene) 0.210 (quarter scene)	$0.444	$0.444		$0.00003	
Data Cost per Scene (Digital Data)	$660	$3300 (full scene) $1650 (quarter scene)	$1600	$1600		$150	

B.2 *Present Earth Resources Satellites*

Landsat-1, -2, -3

For purposes of this discussion, Landsat-1 (launched in July 1972), Landsat-2 (March 1975) and Landsat-3 (March 1978) are treated as identical, successive systems providing continuous data until Landsat-3's retirement in September 1983. Each satellite orbited the earth, once every 103 minutes and at an altitude of approximately 915 kms (540 miles).

As shown in *Figure B.1*, 14 southbound (descending) daytime orbit segments were covered in Landsats 1,2,3 during a single day; northbound (ascending) orbit segments covered the dark side of the earth. The satellite orbit shifted westward one complete path each day; at the end of 18 days, or 252 orbits, the cycle for complete earth coverage began again.

A four-channel, MSS imaged a 185 km swath, subsequently framed to produce scenes covering 185 x 185 kilometers (115 x 115 statute miles). Image acquisition time occurred at the same time of day, at approximately 9:42 a.m. local time, and the repetitive orbit provided the potential for acquiring images from a single satellite every 18 days. Unique to Landsats 1,2, and 3 was the fact that successive orbits matched successive days, as shown in *Figure B.2*. This does not apply to Landsats 4, 5 (see *Figure B.3*).

The Landsats 1,2,3 multispectral scanner acquired data in four spectral bands: 0.5-0.6 um (green), 0.6-0.7 um (red), 0.7-0.8 um (near-infrared), and 0.8-1.1 um (near-infrared). The minimum resolution element, or "pixel," provided an instantaneous-field-of-view (IFOV) of approximately 79 x 79 meters, or 0.45 hectare (1.1 acre); digital processing techniques enable data resampling to a 57 x 57 meter pixel. Each MSS image is composed of approximately 7.6×10^6 pixels per spectral band, totaling 30.4×10^6 pixels per scene.

In addition to the multispectral scanner, Landsat's 1,2,3 carried Return Beam Vidicon (RBV) systems that are similar to television cameras. Landsat's 1 and 2 each carried three RBVs that recorded green, red, and near-infrared images of the same ground area, and produced false-color infrared images comparable to MSS images. Due to technical problems, the RBV images were inferior to MSS images, and only a few RBV images were acquired.

Landsat-3 also carried an RBV sensor system consisting of a pair of cameras acquiring panchromatic imagery with a spectral range of 0.5-0.75 um. Each scene covered 99 km x 99 km, corresponding to MSS quadrants, with a 40 m ground resolution.

Subsequent Landsats have discontinued the RBV systems.

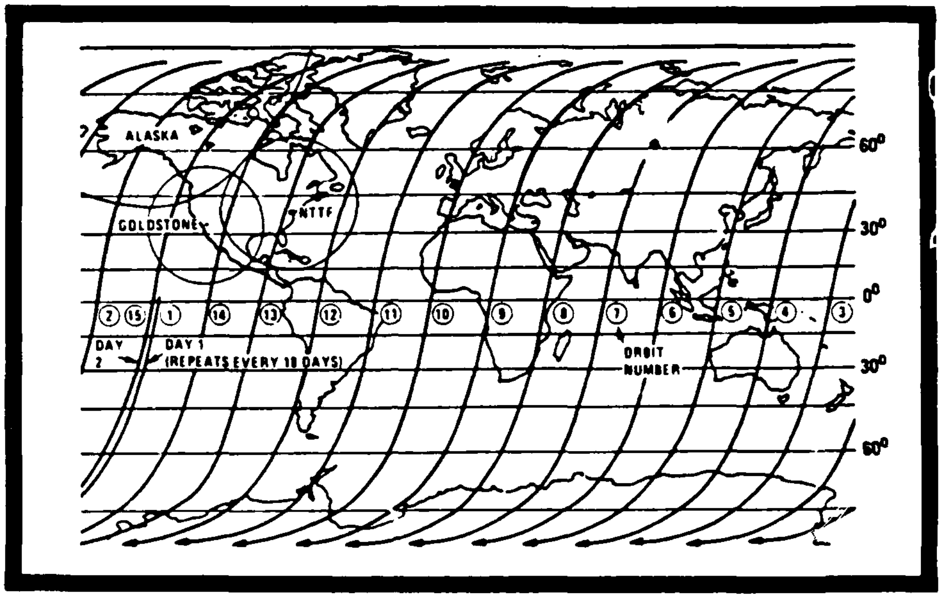


FIGURE B.1. Daytime portion of orbits for Landsats 1, 2, and 3 for a single day. Each day the orbits shift westward 160 km at the Equator to cover the Earth in 18 days. Receiving ranges are shown for MSS ground stations in the United States. From NASA (1976, Fig. 2.7).

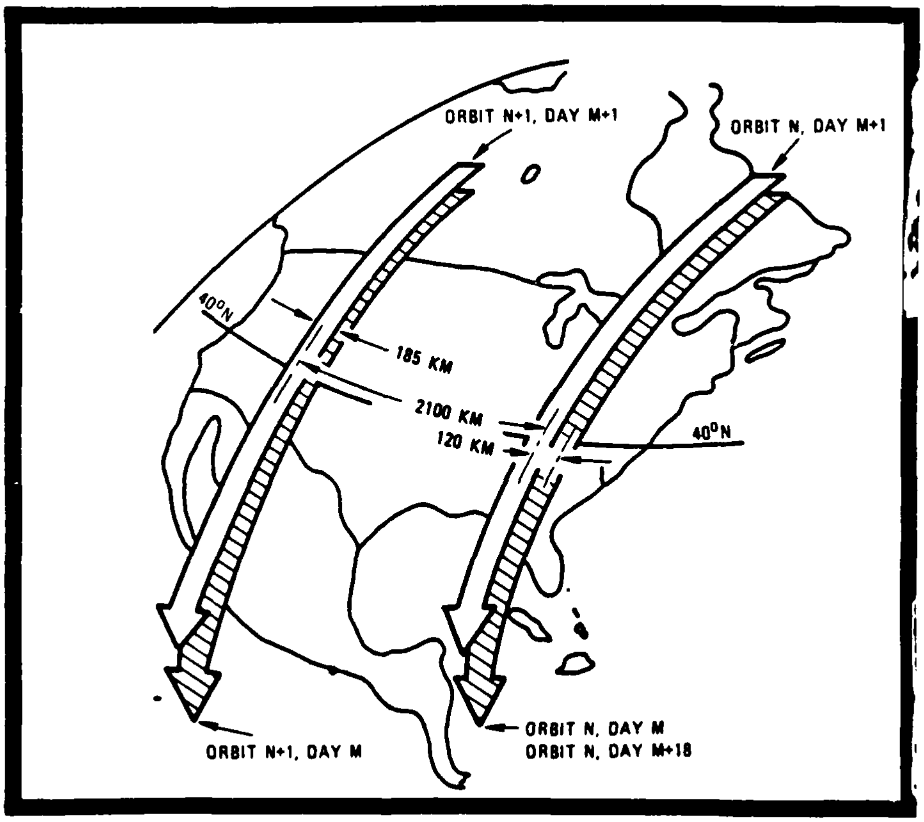


FIGURE B.2. Landsat orbits over the United States on successive days. Note the 62-km sidelap of successive image swaths at 40°N latitude.

WB3233

Landsat-4 and -5

Landsat's second generation of sensors were included on Landsat-4, launched in July 1982, and Landsat-5, launched in March 1984. These satellites are larger and more complex than the first generation predecessors and include, in addition to the MSS imaging system, the Thematic Mapper (TM) imaging system.

Landsat's 4 and 5 operate at a lower orbital altitude of 705 km, resulting in only 233 orbits and 16 days for entire earth coverage. Sidelap of adjacent image swaths is reduced to only 7.6 percent at the equator, compared to 14 percent for Landsats 1,2,3. Landsats 4 and 5 orbit paths are parallel but not coincident with Landsats 1,2,3 paths (see ***Figure B.3***). It is noted that this new orbit, in which adjacent paths are not sequential, can create limitations to hydrologic applications for watersheds or hydrologic systems extending beyond a scene's edge.

The MSS sensor on Landsat's 4 and 5 is essentially identical in image characteristics to Landsats 1,2,3, e.g., four spectral bands, 185 x 170 km (reduced from the 185 km along track image dimension of Landsat's 1-3 MSS) area coverage per scene, 59 m x 79 m ground resolution, or pixel size.

Thematic Mapper

Introduction of the Thematic Mapper (TM) on Landsats 4 (July 1982), 5 (March 1984) began a new generation of satellite remote sensing with refined spatial resolution and expanded spectral coverage. Ground resolution of 30 m x 30 m is provided in six spectral bands in the visible and infrared (0.45-0.52, 0.52-0.60, 0.63-0.69, 0.76-0.90, 1.55-1.75, and 2.08-2.35 micrometers) and 120 m resolution in a Thermal infrared band (10.4 to 12.5 micrometers).

Each TM image consists of approximately 6,000 scan lines, with approximately 6,200 pixels along each scan line, compared to approximately 3,000 scan lines with approximately 3,200 pixels per line for MSS data (see ***Figure B.4***). This increased resolution, plus additional spectral bands, provides TM with more than eight times the data than contained in an MSS image.

Each of the six TM visible and reflected infrared bands employs an array of 16 detectors (compared to six detectors for MSS), and unlike the MSS, recording of TM data occurs during both sweep directions. TM data are recorded on an eight-bit scale, compared to a six-bit scale for MSS bands 4,5, and 6, and six-bit for MSS band 7; this provides TM a greater dynamic range than MSS.

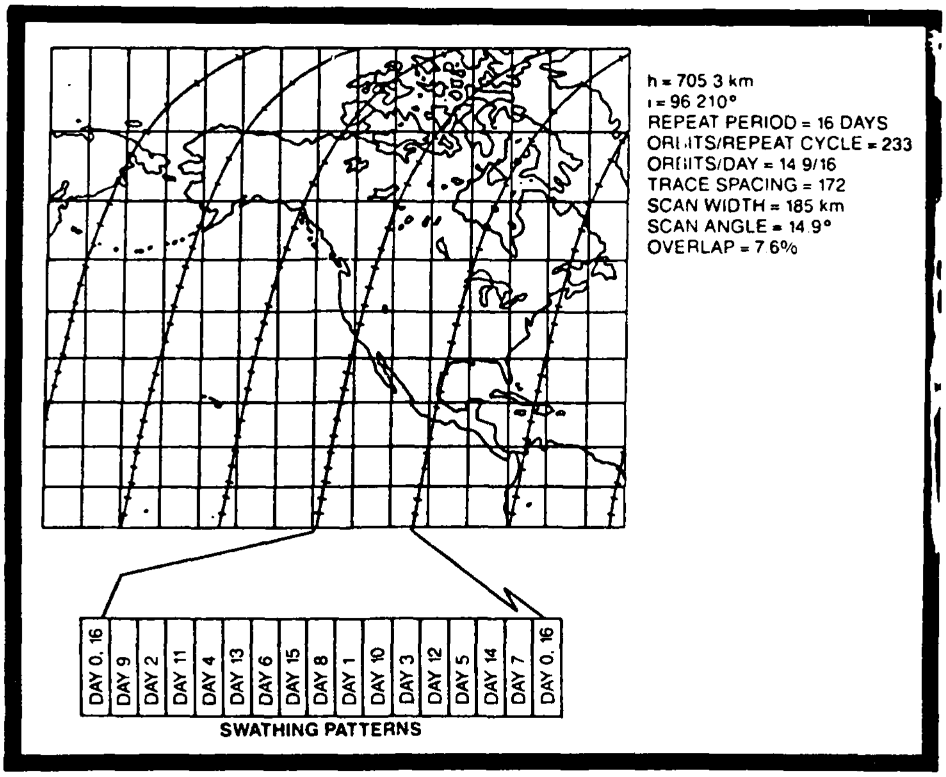


FIGURE B.3. Landsat 4 and 5 orbit ground trace pattern (Source: Landsat Data Users Notes, Issue 35, March, 1986, p. 4).

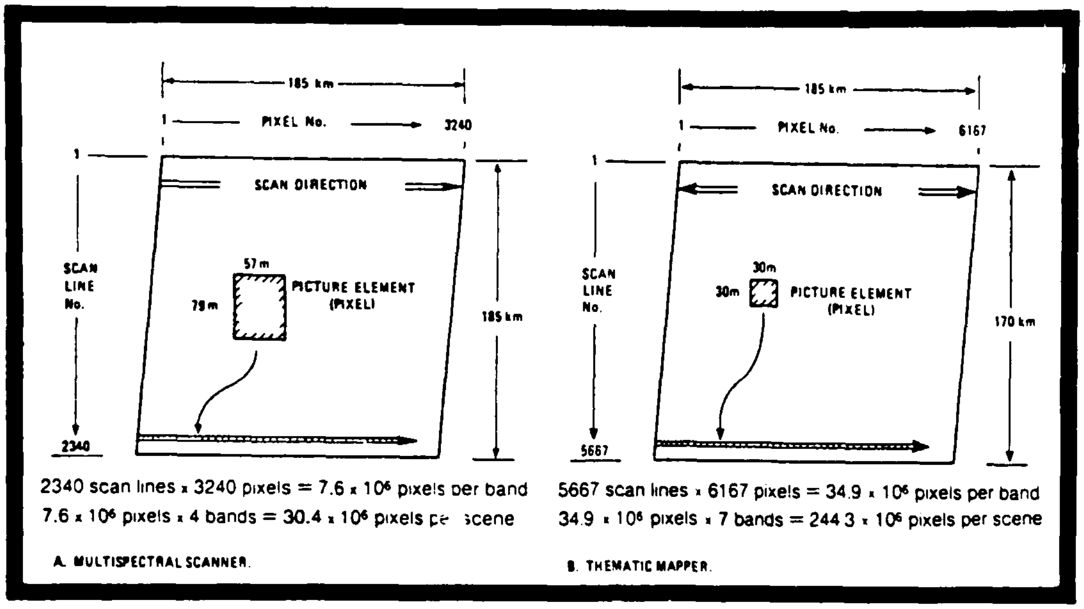


FIGURE B.4. Arrangement of scan lines and pixels in Landsat MSS and TM images.

WB 3234

SPOT

SPOT-1, the first non-U.S. earth resources satellite program, was launched by the French on February 21, 1986. Following an inflight commissioning and performance evaluation period, SPOT began operational status on May 6, 1986.

SPOT-1 orbits the earth at a mean altitude of 832 km. SPOT-1's orbital path consists of 369 satellite tracks, requiring an orbital cycle of 26 days. A significant feature, however, is a steerable mirror that can be tilted from side-to-side to target any area within a 950 km wide area along the satellite's orbit (***Figure B.5***). The mirror-pointing capability means zones of interest can be imaged more frequently than once every 26 days. For example, an area at the equator can be targeted seven times during an orbit cycle, while a zone at 45 degrees latitude can be imaged eleven times during the orbital cycle. This mirror pointing capability also enables SPOT-1 to acquire stereo images by combining two images of the same area recorded during different orbits, at different viewing angles.

Similar to Landsat, the SPOT-1 orbital cycle is designed so that the satellite repeatedly crosses the same latitude at the same mean solar time each day. The geometric relationship between the orbits descending path and the mean projection of the sun onto the equatorial plane is constant. Over the equator, SPOT-1 passes at a mean solar time of 1030 hours each day (***Figure B.6***).

The following example illustrates how to determine the approximate local time SPOT-1 will pass over a given location. The graph in Figure B.6 is used to transform mean solar time into universal time to account for the difference in longitude between the satellite position and the original meridian in the Greenwich Time Zone. Universal time is then converted to local time, as shown.

Example: Time that SPOT-1 passes over Sacramento, CA
Longitude 121°30'W = 121.5°
Latitude 38°40' = 38.67°
Time zone (difference from Greenwich) 12-8=4

1. Mean solar time of SPOT pass (from graph): 1100 hours

2. Difference between universal time and mean solar time: 8 hours

   $\frac{121.4}{360°}$ (longitude) x 24 hours = 8.1 hours = 0806

3. Universal time of SPOT pass:
   1100 + 0806 = 1906 hours

4. Local time = universal time of SPOT pass - time zone difference.

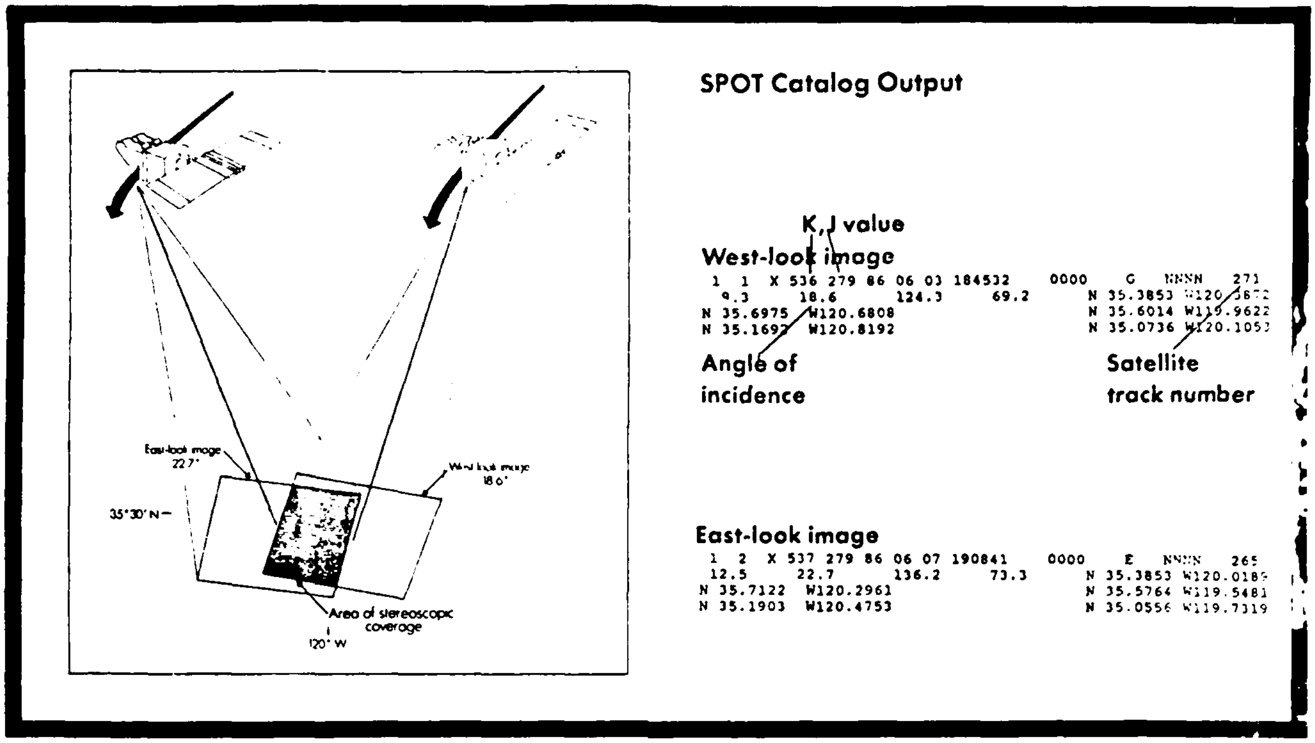


FIGURE B.5.

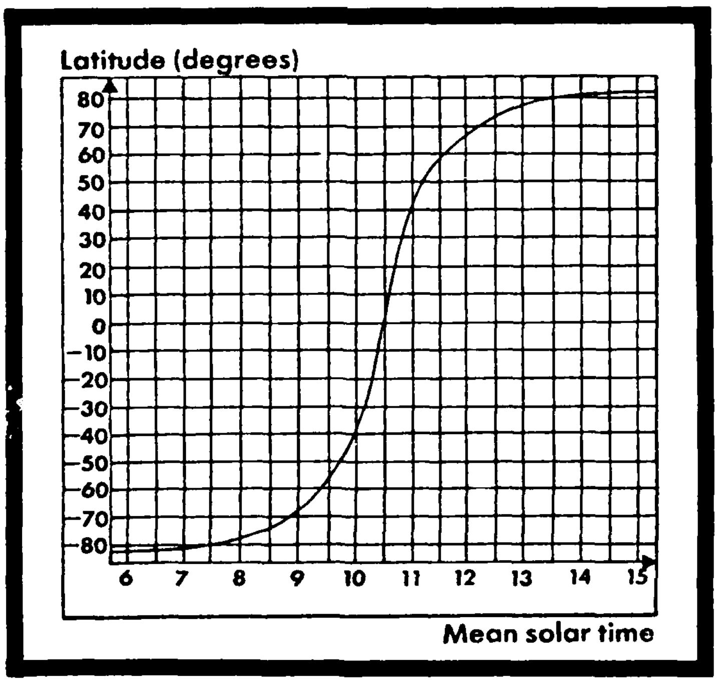


FIGURE B.6. Local solar time of SPOT pass

WB 3235

Local time = 1806 - 8 hours = 10:06 a.m.

Because of the off-nadir viewing capability, SPOT does not need to pass directly over an area to acquire an image. The number of image acquisition opportunities is determined by the latitude of a site, with orbital tracks converging at higher latitudes. While the latitude remains the same for off-nadir viewing of a site, the longitudinal position of the satellite varies and can be accounted for with the above calculations.

SPOT-1 sensors include two high resolution visible (HRV) instruments using a "push-broom" scanner to record image data. An array of 6,000 detectors are linearly arranged, forming the push-broom scanner, which images a complete line on the ground without mechanical scanning. The next line is recorded as the satellite advances along its orbit path (Courtois and Weill, 1985).

The High Resolution Visible (HRV) instrument may operate in two modes. In the multispectral mode, imagery is acquired in three spectral bands (0.50-0.59 um, 0.61-0.68 um and 0.79-0.89 um) with 20 m ground resolution. Each multispectral image covers a 60 km x 60 km ground area (nadir viewing) with 3,000 pixels along each of 3,000 lines. In the panchromatic mode, imagery is acquired in a single broad band (0.51-0.73 um) with 10 m ground resolution. Each panchromatic image also covers a 60 km x 60 km ground area (nadir viewing), with 6,000 pixels along each of 6,000 lines.

MOS-1

On February 23, 1987, the Japanese successfully launched the Marine Observation Satellite-1 (MOS-1) into a polar sun-synchronous orbit. The primary objectives of MOS-1 are to measure oceanographic phenomena, and at the same time provide an experimental platform for basic earth observation technology development by the Japanese remote sensing industry. MOS-1 was launched into a 909 km altitude with an inclination of approximately 99 degrees. It orbits the earth 14 times a day, with complete earth coverage/revisit cycle each 17 days. In this, and additional respects, MOS-1 is very similar to the Landsat 1,2,3 series, but with 50-meter resolution.

MOS-1 sensor include a Visible and Thermal Infrared Radiometer (VTIR), a Multispectral Electronic Self-Scanning Radiometer (MESSR), and a Microwave Scanning Radiometer (MSR); characteristics of MOS-1 sensors are shown on ***Figure B-7.*** In addition, a Data Collection System Transponder (DCST) provides data relay from a variety of data collection platforms (DCP's).

The VTIR system uses a scanning mirror to measure a 1,500 km swath width in four spectral bands of visible light and infrared radiation: 0.5-0.7 um (green, red) with 0.9 km resolution; 6.0-7.0 um (infrared), with 2.7 km resolution; 10.5-11.5 um and 11.5-12.5 um (thermal IR), both with 2.7 km resolution. This is the primary instrument for sea surface color and temperature measurement objectives.

The MESSR system utilizes a CCD sensor to perform electronic scanning without a scanning mirror, covering a 100 km swath with four spectral bands identical to Landsat MSS: 0.51-0.59 um (green), 0.61 um (red), 0.72-0.80 um (near-IR) and 0.80-1.10 um (near-IR). Resolution of 50 meters, represents a 60 percent improvement over MSS with a swath width similar to SPOT (e.g., 60 km).

The MSR system can measure microwaves emitted from the earth surface and the atmosphere at two frequencies, 24 GHz (31 km resolution) and 31 GHz (21 km resolution). The MSR is a day-night all weather system that penetrates cloud cover. The primary design objective is measurement of atmospheric liquid water content, moisture content, and sea ice and snow distribution. The recording swath width will be 320 km.

MOS-1 data are transmitted to a ground receiving station in Japan; additional ground stations are under construction (see Section B.5). Reception by the Gatineau, Canada station will provide coverage for the eastern U.S. beginning in mid-1988. MOS-1 data are available through the Remote Sensing Technology Center of Japan (RESTEC). MOS-1 will be followed by the planned launch of MOS-1b, scheduled for early 1989.

Item \ Sensor	MESSR	VTIR		MSR	
Measurement Objective	Sea-surface colour	Sea-surface temperature		Water content of atmosphere	
Wavelength (μm)	0.51 to 0.59 0.61 to 0.69 0.72 to 0.80 0.80 to 1.1	0.5 to 0.7	6.0 to 7.0 10.5 to 11.5 11.5 to 12.5	–	
Frequency (GHz)	–	–	–	23.8	31.4
Geometric Resolution (IFOV in km)	0.05	0.9	2.7	32	23
Radiometric Resolution	(39 dB)	55 dB* (Albedo = 80 per cent)	0.5 K	1 K	1 K
Swath width (km)	100 (one optical element) x 2	1,500		320	
Scanning Method	electric	mechanical		mechanical	

Remarks * Signal-to-noise ratio excluding quantization noise.

FIGURE B-7. Characteristics of MOS-1 sensors.

B.3 Future Planned Earth Resources Satellites

Landsat-6 - ETM

The Earth Observation Satellite Company (EOSAT) presently plans to launch Landsat 6 in first quarter of 1991. The principal sensor will be an Enhanced Thematic Mapper (ETM) scanner. The ETM will be mechanically identical to the current TM scanners. However, significant additions will be made to instrument's focal planes. In addition to the existing six 30-meter spectral bands, the ETM will also have a 15-meter panchromatic band with a spectral range between 0.5 and 0.90 micrometers. The panchromatic detectors will co-habitate the same focal plane as the 30-meter bands allowing systematic coregistration of the two data sets. In addition, Landsat-6 may also carry four multispectral thermal bands with a 60 x 60 meters ground resolution, and a 120-meter band, centered at 3.5 micrometers, replacing the present 120-meter thermal TM band at 10-12 micrometers.

SeaWiFS

In September 1987, EOSAT announced the addition of the "SeaWiFS" sensor to Landsat-6. The sea-viewing, Wide-Field of View Sensor (SeaWiFS) combines attributes of data gathered by the Coastal Zone Color Scanner (CZCS), which operated from 1978-1986, and the Advanced Very High Resolution Radiomater (AVHRR) which is operated on NOAA polar orbitor satellites (Section 4.2.4). The sensor will provide 4 visible, 2 near-IR, and 2 thermal IR spectral channels, near-daily local-area data with a 1.13 km resolution, daily global area coverage with a 4.5 km resolution, and a swath-width of 2400 km.

SPOT-2 - SPOT IMAGE

Because of the successful performance of SPOT-1, its operational life expectancy has been extended from the two years to three years, through February 1989. SPOT-2, which is identified to SPOT-1, has been constructed and is presently in storage in Toulousse, France. It is presently planned for launch in early 1989, but may be launched sooner in the event SPOT-1 develops data acquisition or transmission problems.

SPOT Image S.A. is committed to a policy of continuous data through the end of the century. SPOT-3 (also identical to SPOT-1, -2) and an upgraded SPOT-4 have been approved for construction.

While upgrade characteristics for SPOT-4 are still under study, several design consideration have been announced:

- o A fourth multispectral band (20 m. resolution) will be added in the near-infrared region (1.6 u).
- o On board registration of panchromatic (10 m) and multispectral (20 m) data.

- A new Vegetation Sensor, with four multispectral bands, a 2000 km field of view at 1 km resolution, for daily or bi-daily wide area coverage, designed for global vegetation/crop assessment and monitoring.

J-ERS-1

The Japan Earth Resources Satellite-1 (J-ERS-1) is the second series of planned Japanese satellite, to follow MOS-1 with a launch in 1992. The J-ERS-1 objectives will include earth observation data for resource investigations, forestry, agriculture and aquaculture applications, etc. ERS-1 is planned for a near-polar sunsynchronous orbit at 570 km altitude.

Planned J-ERS-1 sensors include a Synthetic Aperture Radar (SAR) for geologic applications, a Visible and Near-Infrared Radiometer (VNR) for vegetation/resource distribution objectives, and a Short-Wave Infrared Radiometer (SWIR) for discriminating rock types, as shown in ***Figure B-8***.

Item \ Sensor	SAR	OPS			
		Band	Centre wavelength	Band width	Notes
Wavelength (μm)	L-band	1	0.56	0.08	
		2	0.66	0.06	
		3	0.81	0.10	
		4	0.81	0.10	Band 4 is for off-nadir viewing.
		5	1.655	0.11	Bands 3 and 4 make a stereo-pair.
		6	2.065	0.11	
		7	2.19	0.12	
		8	2.335	0.13	
Polarization	H – H	–			
Band number	1	8 (approximately)			
Spatial resolution (sq m)	18 (approximately) (3-look)	18 x 24 (approximately)			
Off-nadir angle (degrees)	35	15.33 (Band 4 only)			
Swath width (km)	75 (approximately)	75 (approximately)			
Stereoscopic imaging capability	–	Yes			

FIGURE B-8. Basic specifications of J-ERS-1 sensors.

The SAR will be an active microwave imaging sensor which transmits pulses diagonally to the earth's surface and detects reflected waves from the surface. It will use L-band (24 cm wavelength), with H-H polarization, providing all-weather imaging capabilities.

The VNR will provide multispectral imaging in four bands: 0.45-0.52 um, 0.53-0.60 um, 0.63-0.69 um, and 0.76-0.90 um. In addition to vertical downward viewing, a forward-looking sensor called a three-dimensional band is planned. Combining the vertical-looking image with the forward-looking image will provide a stereo capability.

The SWIR will also provide multispecti l sensing with three or four bands centering on the following infrared frequencies: 1.65 um, 2.10 um, 2.20 um, and 2.35 um.

All three sensor systems on J-ERS-1 are expected to acquire image data over a 75 km swath width with a 20-meter resolution.

MECB - Brazil

In 1980, the Brazilian government authorized the development of a series of four Brazilian satellites, collectively referred to as MECB (Missao Especial Completa Brasileira). Preliminary details were announced in 1986 by INPE who is responsible for the design, construction, and operation of the satellites.

The first two missions will provide Data Collection Satellites in an orbital altitude of 700-800 km. These satellites will collect and re-transmit meteorological and hydrological data from ground-based Data Collection Platforms distributed throughout Brazil. The first launch is planned in the early 1990's.

Subsequently, two Remote Sensing Satellites are planned, providing multispectral imaging capabilities from an orbital altitude of 642 km. A multispectral sensor will provide data in three bands, (1) .470-.530 um, (2) .630-680 um, and (3) .830-910 um, with 40 m. resolution. Image area will be approximately 80 km x 80 km. In addition to vertical (nadir) viewing, lateral viewing of up to 15 degrees from vertical is included in the design.

ERS-1, -2

The European Remote Sensing Satellite (ERS) presently constitutes the most significant activity of the European Space Agency (ESA) in the earth observation field. The planned ERS mission is designed principally for ocean and ice monitoring. The first satellite, ERS-1, is planned for an early 1991 launch, with a three-year life time. A second model, ERS-2, is expected to be launched in 1993 to perform continuous operation until 1996.

The ERS-1 and ERS-2 spacecrafts will be polar orbiting and will contain three core instruments:

- a radar altimeter

- an active microwave instrument with a C-band wind scatterometer and a C-band synthetic aperture radar (SAR)

- a laser retroreflector.

These instruments will be complemented by two nationally provided instruments:

- an along-track scanning radiometer jointly provided by UK and France.

- a precise range and range rate experiment provided by FR Germany.

In addition, at the European Space Agency Ministerial Council in January 1985, a long-term space plan was approved that included implementation of an ERS-2 program for launch in 1993.

IRS

The Indian Remote Sensing Satellite System (IRS) was announced by the Indian Space Research Organization, Bangalore, in June 1986. The program is expected to consist of a series of satellites, with the first, IRS-1A originally scheduled for launch in mid-1987; current status of launch plans are not available as of December 1987.

According to Indian announcements, the IRS will be in a 904 km near circular sun-synchronous orbit with a 22-day repeat cycle. Sensors systems will consist of three Linear Imaging Self Scanning Cameras (LISS) using CCD sensors. Each camera will acquire data in four bands: 0.45-0.52 um, 0.52-0.59 um, 0.62-0.68 um, and 0.77-0.86 um. The first camera, LISS-1, will provide 73-meter resolution in a 148 km swath width. The second and third cameras, LISS-IIA and LISS-IIB, are identical systems arranged for individual swaths of 74 km on either side of the ground track, with 36.5 meter resolution.

RADARSAT - Canada

Canada is proceeding with the RADARSAT satellite, set for launch in 1994. RADARSAT will provide SAR data for all-weather sea ice monitoring.

B.4 *Environmental Satellites*

NOAA Polar Orbiting Satellites

For many years NOAA has operated a system of polar orbiting operational satellites, some of them crossing the equator in the morning, others crossing in the afternoon. The latest satellite of this system was launched in September 1986. NOAA intends to launch further identical satellites and to continue providing data services.

AVHRR

The Advanced Very High Resolution Radiometer (AVHRR) is a five channel instrument designed to provide large area information on cloud systems, snow and ice cover, land and sea-surface temperature, vegetation, etc. The AVHRR instrument flies on board the polar-orbiting NOAA series of satellites; NOAA-8 and NOAA-9 are currently active in near-polar (99° inclination), sun-synchronous orbits.

Equatorial crossings take place at 0738 and 1938 hours local time for NOAA-8, and at 0242 and 1442 hours local time for NOAA-9. Each satellite completes 14.2 orbits per day at an altitude of approximately 830 km.

The AVHRR acquires data in four spectral regions visible (0.58-0.68 um), near-infrared (0.725-0.10 um), thermal mid-infrared (3.55-3.93 um), and two thermal far-infrared (10.5-11.5 um and 11.5-12.5 um), using real-time High Resolution Picture Transmission (HRPT). In the U.S., data are received at Wallops Island, Virginia, Redwood City, California, Sioux Falls, South Dakota, Gilmore Creek, Alaska and others.

The NOAA-8 AVHRR acquires data with 1.1 km resolution in all spectral channels, over a swath width of 2,940 km. On NOAA-9, the AVHRR resolution is 0.5 km in the visible channel, and 1.0 km in the infrared channels, with a swath width of 2,600 km. Although the orbit repeat cycle requires nine days for nadir viewing, the wide, overlapping swaths provide daily coverage.

Geostationary Meteorological Satellites (GOES/VAS)

Worldwide meteorological observations are presently performed on a global basis by geostationary operational satellites GOES-East and GOES-West of NOAA, Meteosat of the European Space Agency, and GMS of the Japanese Meteorological Agency, provide similar data for most of the earth's surfaces on a continuous and operational basis. These systems are foreseen to continue with new, more advanced systems planned or underdevelopment. Data from geostationary spacecraft are complemented by the operational polar orbiting system of NOAA.

NOAA's geostationary operational environmental satellite (GOES) system has been operational for many years. The most recent unit, GOES-G, was successfully launched in March 1987.

Two Geostationary Operational Environmental Satellites (GOES) (*Figure B.9*) monitor the eastern and western United States from their positions over the equator (*Figure B.10*). They are centered at 75°W and 135°W. Using the VAS (Visible Spin Scan Radiometer and Atmospheric Sounder) they can make half hourly weather observations day and night. The VISSR collects 1-8 km resolution data at 0.54-0.70 um (daytime) and 10.50-12.60 um (nightime and daytime) thermal data for hurricane and severe storm monitoring. It can also send weather facsimiles (WEFAX) to military ships and overseas bases. In the Atmospheric Sounder mode it can gather IR radiation data in 12 spectral bands for use in producing atmospheric temperature profiles and moisture measurements. DOD has several GOES Direct Readout Stations (*Figure B.11*: Omaha, Nebraska, Monterey, California, White Sands, New Mexico and Bedford, Massachusetts. Shared processing centers for data interlinked through domestic commercial satellites are at FNOC, Monterey, California; AFGWC, Offut, Nebraska; and NOAA, Suitland, Maryland; and Wallops Island, Virginia.

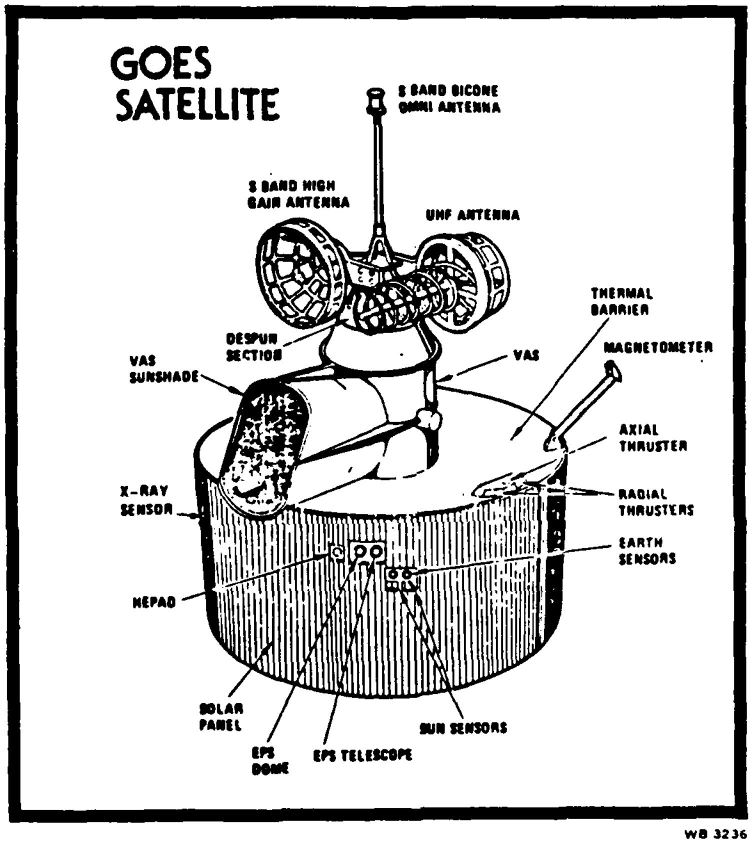
Half-hourly enhanced IR imagery is available through the NOAA Interactive Flash Flood Analyzer (IFFA). It is used to estimate precipitation amounts in both convective and non-convective situations. Isopleth maps are based on the improved Scofield-Oliver Technique, and the estimates are disseminated via AFOS to NWS offices as guidance for issuing flash flood watches and warnings (*Figure B.12*).

Defense Meteorological Satellite Program (DMSP)

In addition to the NOAA Tiros-N series of polar-orbiting satellites, another weather satellite system is operated by DOD, the Defense Meteorological Satellite Program (DMSP). The satellite itself is similar to the Tiros-N, but the instrumentation is different (Table 1.1). One of its newer instruments, just recently placed in orbit, is the Special Sensor Microwave Imager (SSM/I). The SSM/I is capable of providing all-weather measurements of ocean surface wind speed, sea and lake ice information, and precipitation amount as well as estimates of soil moisture.

The SSM/I has a 1400 km swath width. It is a passive imager with seven channels in four frequencies 19.35, 37.0, and 85.5 GHz (all with both horizontal and vertical polarization) and one (22.23 GHz) with vertical polarization only. It is of interest to note that NOAA/NESDIS will be responsible for the data processing (for soil moisture of the SSM/I data by agreement among the Air Force Global Weather Central (AFGWC), the Fleet Numerical Oceanography Center (FNOC) and the NOAA/National Environmental Satellite and Data Information Service (NESDIS). FNOC will also process the SSM/I data but only for ocean wind speed and sea ice information.

DOD does not archive the environmental satellite data it collects but rather it transmits these data to NOAA for archiving. Copies of DMSP imagery and DMSP space environmental data are sent to the NOAA archive in Boulder, Colorado.


GOES
SATELLITE
S BAND BICONE
OMNI ANTENNA
S BAND HIGH
GAIN ANTENNA
UHF ANTENNA
THERMAL
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SECTION
VAS
VAS
SUNSHADE
MAGNETOMETER
AXIAL
THRUSTER
RADIAL
THRUSTERS
X-RAY
SENSOR
EARTH
SENSORS
HEPAD
SOLAR
PANEL
SUN SENSORS
EPS
DOME
EPS TELESCOPE
WB 3236

FIGURE B.9.

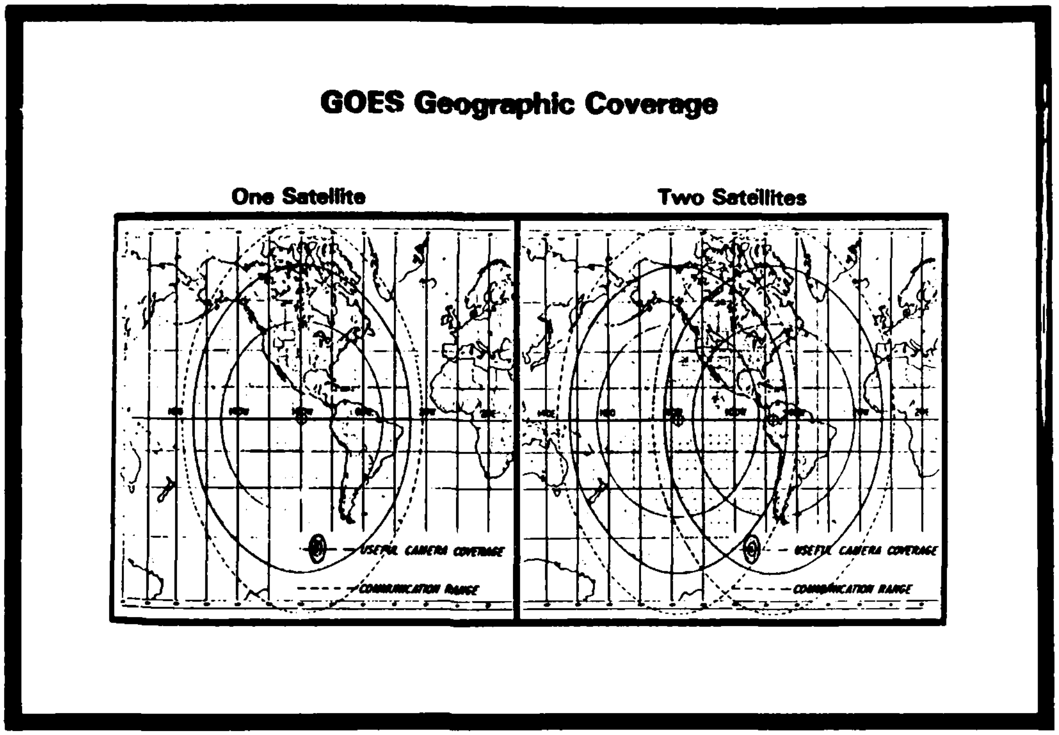


FIGURE B.10.

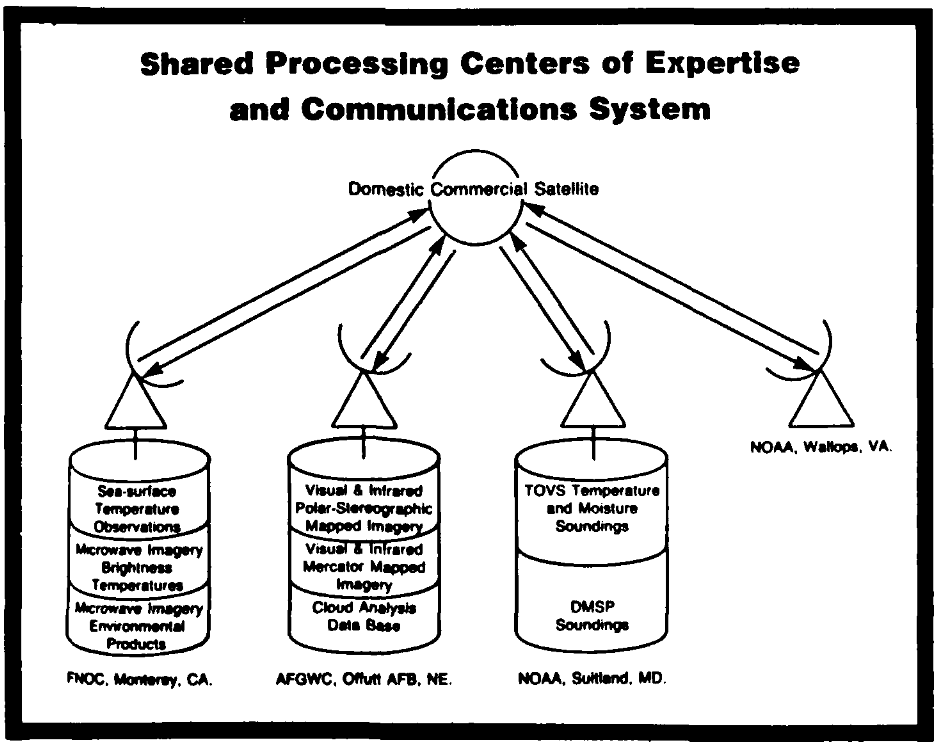
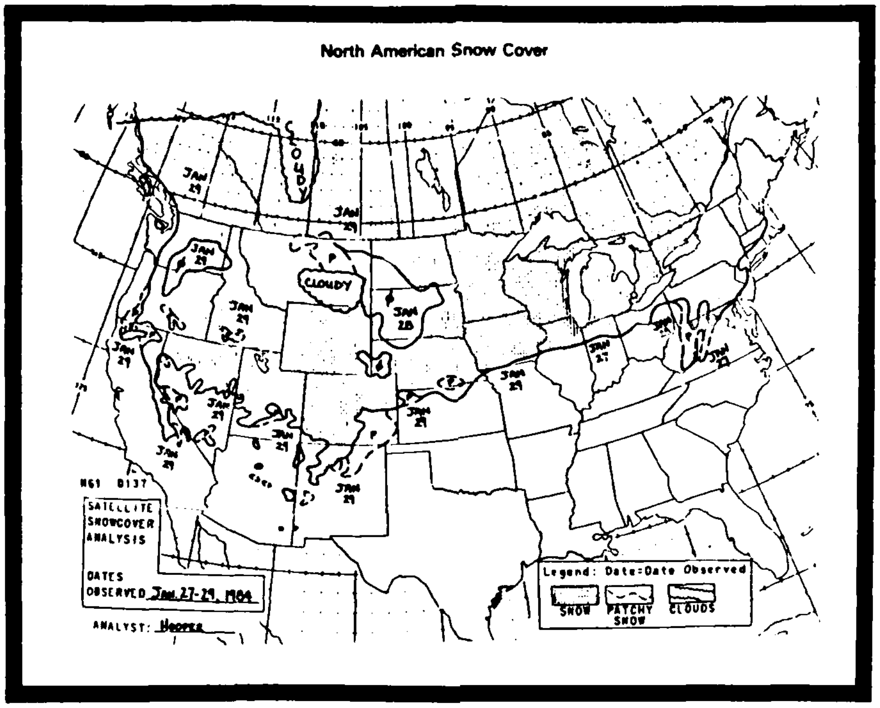


FIGURE B.11.

WB 3237



Satellite Precipitation Estimates

NFDSPELA
WOUS00 KNFD 231200

SATELLITE PRECIPITATION ESTIMATES... DATE/TIME OF MESSAGE 10/23/84 1040Z
PREPARED BY THE SYNOPTIC ANALYSIS BRANCH/NESDIS TEL. 763-8444
QUANTITATIVE VALUES REFLECT MAXIMUM OR SIGNIFICANT ESTIMATES. OROGRAPHIC
EFFECTS ARE NOT ACCOUNTED FOR.
LATEST SATELLITE DATA USED: 231030Z CK

LOCATION	HR RATE	TOTALS TIME TIME CORREC	REMARKS
LA PARRISHES...	09-10Z	07-10Z	1030Z SHWS CNTNUED
LAFAYETTE	0.9*	3.0*	WRNG OF CNVCTV AREA.
VERMILLION	0.6	2.0	COLD CELLS WHICH
W ST. MARTIN	0.9	2.3	CROSSED CSTL CAMERON
S ST. LANDRY	0.5	2.2	AT 10Z MVD RPDLY NE AT
IBERIA	0.5	1.6-2.3(NW)	1030Z. NOTE: CNVTN
NW ST. MARY	0.5	1.7	OVR GULF PERSISTS SO
CAMERON	0.9COAST	1.5(E)-2.0(COAST)	THERE CUD BE MORE TO
			COME...

FIGURE B.12.

WB 3238

European Space Agency (ESA)

After the successful launch of two pre-operational meteorological satellites, Meteosat 1 and 2, in 1977 and 1981 respectively, ESA is presently planning to launch the phototype P2 by early 1988. This satellite is supposed to provide continuity of data to the European Meteorological Services until the first satellite of the operational series is launched. The Meteosat Operational Programme (MOP) will provide operational continuity until approximately 1995, with the following planned satellite launches: MOP-1 in September 1988, MOP-2 in January 1990; and MOP-3 in January 1991.

Japan

Two geostationary meteorological satellites (GMS) have been launched to date. GMS-2, launched in 1981, operated only for six months; GMS-3, launched in 1984, is still operational with some degradation. The Japanese Meteorological Agency (JMA) plans to have a new satellite system operational by 1989.

B.5 Satellite Ground Receiving Stations

The early Landsat satellites contained tape recorders in order to collect data over areas beyond the receiving range of earth-based stations. Subsequent satellites, including all of the current earth resources satellites, transmit acquired data in real-time. This has led to development of a network of ground receiving stations worldwide. In addition, Landsat 4, 5 can acquire data outside of receiving station range by relaying data through a TDRISS data relay satellite; presently, one TDRISS is in geostationary position over the equator at approximately 35° West longitude, providing Landsat data acquisitions for North and South America, Europe, Africa, and the Middle East.

Fifteen countries have constructed ground systems to receive and process data directly, and other stations are in the construction or planning stages. ***Figures B.13, B.14, and B.15*** shows the location and coverage areas for the existing network of ground stations, and their data receiving capabilities (e.g., Landsats 4, 5 MSS & TM, SPOT-1 and MOS-1). Image data are processed and archived at each receiving station, and requests for data must be addressed to each respective station.

Upgrades of receiving station capabilities are both ongoing and planned. For example, in November-December 1987, the Thailand receiving station was undergoing modifications to receive Landsat TM, SPOT, and MOS-1 data; previously only Landsat MSS data were acquired. During the next year, several additional stations will be upgraded to receive SPOT and MOS-1 data, as shown on the corresponding figures.

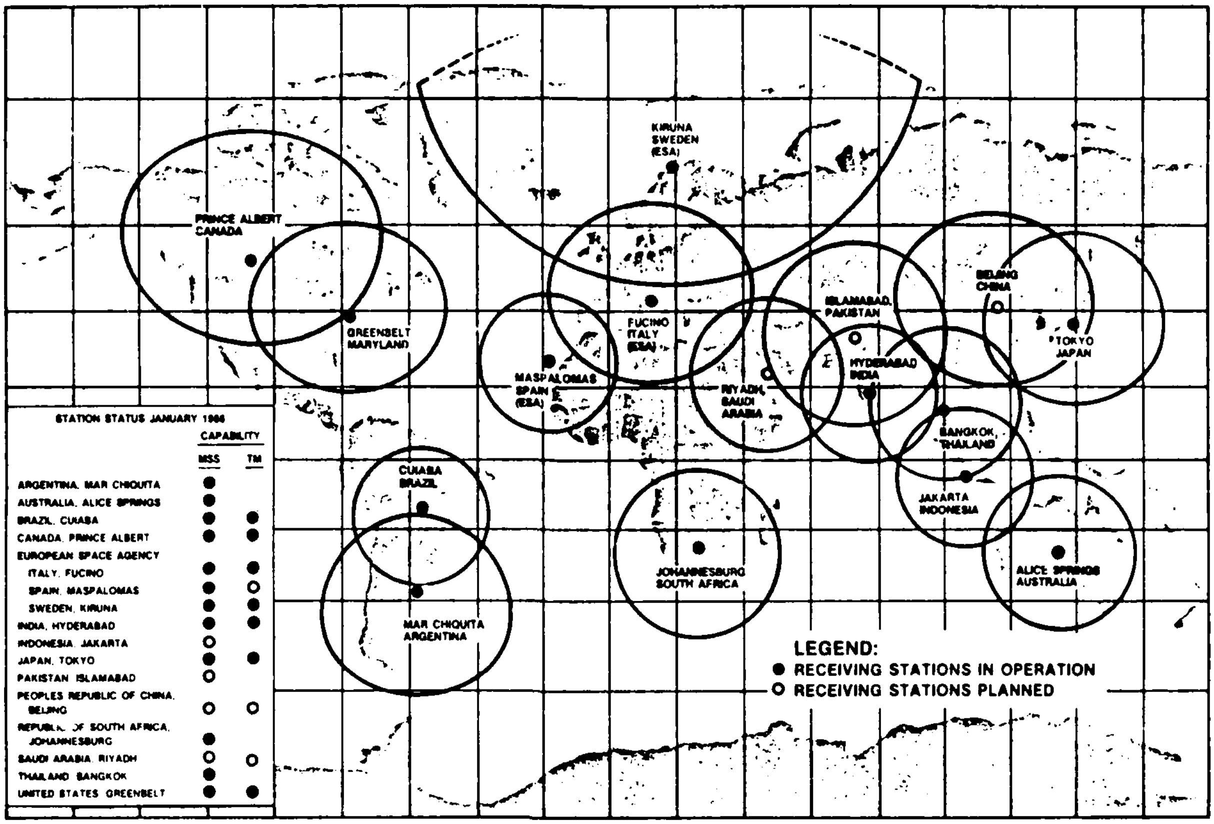


Figure B.13: Landsat Receiving Station Coverage

Station	Date	Capability	Status
Argentina, Mar Chiquita	1980	MSS	Off-line
Australia, Alice Springs	1980	MSS	TM upgrade schedule for 1989
Brazil, Cuiaba	1974	MSS, TM	Operational
Canada, Prince Albert	1972	MSS, TM	Operational
European Space Agency			
Italy, Fucino	1975	MSS, TM	Operational
Sweden, Kiruna	1983	MSS, TM	Operational
Spain, Maspalomas	1984	MSS, TM	Operational
India, Hyderabad	1980	MSS, TM	Operational
Indonesia, Jakarta	1982	MSS	Off-line, TM upgrade announced
Japan, Tokyo	1979	MSS, TM	Operational
Pakistan, Islamabad	1988	MSS, TM	Scheduled for 1988
Peoples Rep. of China, Beijing	1986	MSS, TM	Operational
Rep. of S. Africa, Johannesburg	1980	MSS	Operational, TM upgrade planned for 1989
Saudi Arabia, Riyadh	1987	MSS, TM	Operational
Thailand, Bangkok	1981	MSS	Operational, TM upgrade completed end of 1987
United States, Greenbelt	1972	MSS, TM	Operational

Source: EOSAT Corporation, December 1987.

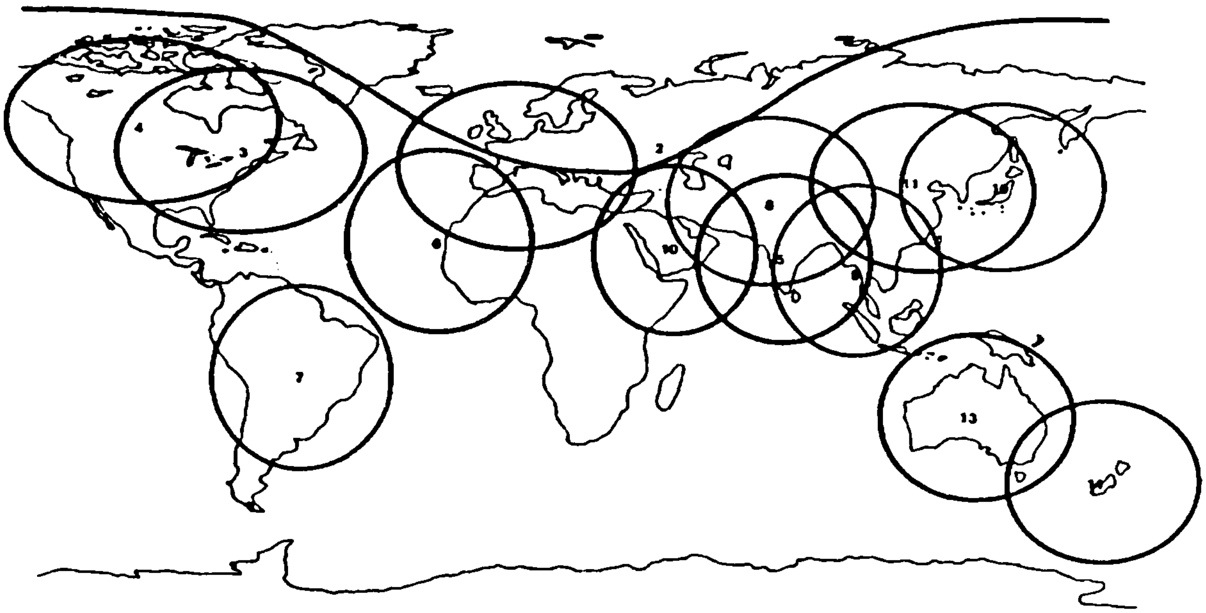


Figure B.14: SPOT Receiving Station Coverage

	Station	Status
1.	France, Toulouse	Operating, February 1986
2.	Sweden, Kiruna	Operating, February 1986
3.	Canada, Gatineau	Operating, August 1986
4.	Prince Albert	Operating, August 1986
5.	India, Hyderabad	Operating, August 1986
6.	Spain, Maspalomas	Operating, October 1987
7.	Brazil, Cuiaba	Under Construction, est. early 1988
8.	Pakistan, Islamabad	Under Construction, est. early 1988
9.	Thailand, Bangkok	Under Construction, est. mid-1988
10.	Saudi Arabia, Riyadh	Under Negotiation, est. 1988
11.	China, Beijing	Under Negotiation, est. 1988
12.	Japan, Tokyo (Hatoyama)	Under Construction, est. end-1988
13.	Australia, Alice Springs	Under Negotiation, est. 1988
14.	New Zealand, Auckland	Under Negotiation, est. 1989

Source: SPOT Image Corporation, Reston, VA, December 1987.

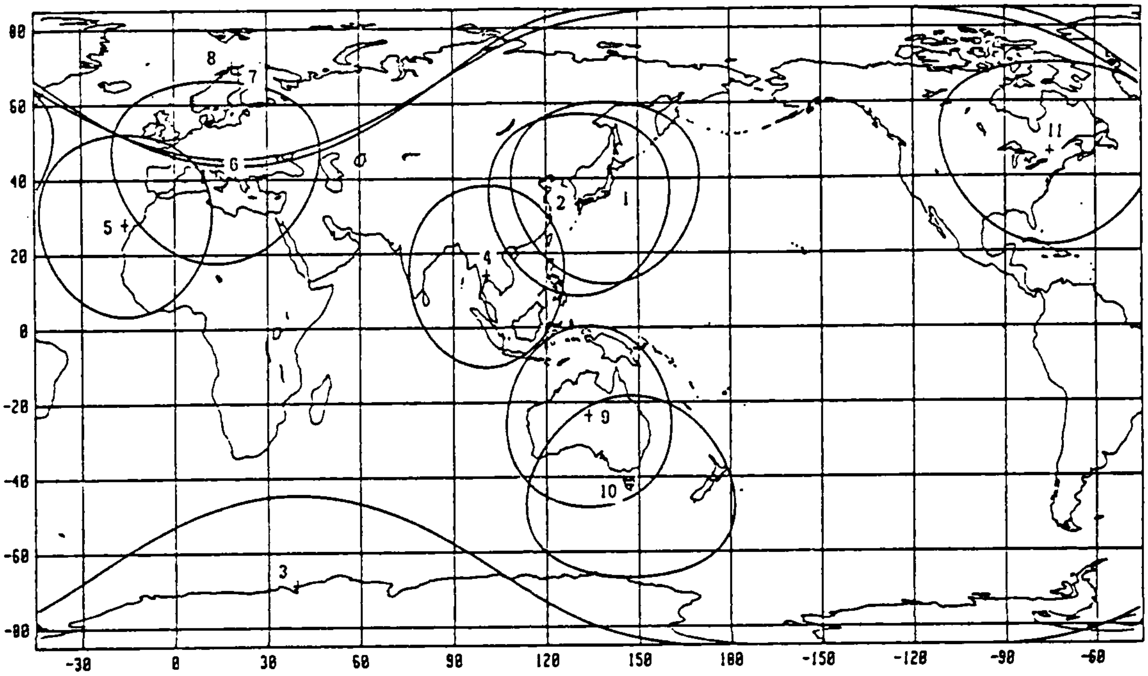


Figure B.15: MOS-1 Receiving Station Coverage

	Station	Status
1.	Japan, Tokyo	Operating, February 1987
2.	Japan, Kumamoto (private)	Operating, May 1987
3.	Antarctica, Shouwa Station	Planned for 1989
4.	Thailand, Bangkok	Planned for April 1988
5.	ESA/Spain, Maspalomas	Test receiving started in
6.	ESA/Italy, Fucino	September 1987; will be
7.	ESA/Sweden, Kiruna	used for demonstration and
8.	Norway, Tromso	verification purposes
9.	Australia, Alice Springs	Planned for April 1988
10.	Australia, Hobart	Planned for April 1988
11.	Canada, Gatineau	Planned for July 1988

Source: RESTEC, Tokyo, Japan, October 1987.

GLOSSARY OF ACRONYMS

AFGWC	Air Force Global Weather Center
AFOS	Advanced Forecasting and Observing System
AVHRR	Advanced Very High Resolution Radiometer
BSQ	Band Sequential
BIL	Band Interleaved By Line
CCT	Computer-Compatible Tape
CROPCAST	EarthSat Crop Forecasting and Information Service
CRREL	Cold Regions Research and Engineering Laboratory (Corps of Engineers)
CUHM	Colorado Urban Hydrograph Method
CZCS	Coastal Zone Color Scanner
DBMS	Data Base Management Systems
DCS	Data Communication Systems
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
EDIPS	EROS Data Image Processing System
EGP	Enhanced Graphics Package
EOSAT	Earth Observation Satellite Company
EPA	Environmental Protection Agency
ERS	European Remote Sensing Satellite
ESA	European Space Agency
EROS	Earth Resources Observation System (U.S. Dept. of Interior, U.S. Geological Survey)
ESMR	Electric Scanning Microwave Radiometer
FEMA	Federal Emergency Management Agency
FNOC	Fleet Numerical Oceanography Center
GEOCODE	Control Point Program
GIS	Geographic Information System
GMS	Japanese Geostationary Meteorological Satellite
GOES	Geostationary Operational Environmental Satellite (NOAA)
HEC	Hydrologic Engineering Center (Corps of Engineers)
HEC/SAM	Hydrologic Engineering Center/Spatial Analysis Methodology
HRPT	High Resolution Picture Terminal
HRV	High Resolution Visible (instruments on SPOT-1)
IFFA	Interactive Flash Flood Analyzer (NOAA)
IFOV	Instantaneous Field of View
IHS	Intensity, Hue, Saturation
IR	Infrared
IRS	Indian Remote Sensing Satellite System
IUH	Instantaneous Unit Hydrograph
J-ERS	Japanese Earth Resources Satellite
JMA	Japanese Meteorological Agency

LEAP	Landsat Emergency Access and Products
LISS	Linear Imaging Self Scanning Cameras (IRS)
MECB	Missao Especial Completa Brasileriva (INPE, Brazil)
MESSR	MOS-1's Multispectral Electronic Self-Scanning Radiometer
METEOSAT	Europe Meteorological Satellite
MOPS	Meteosat Operational Program (ESA)
MOS-1	Japan's Marine Observation Satellite
MSR	MOS-1's Microwave Scanning Radiometer
MSS	Multispectral Scanner
NESDIS	National Environmental Satellite Data Information Service (NOAA)
NESS	National Environmental Satellite Service (obsolete, now NESDIS)
NEXRAD	Next-Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
RBV	Return Beam Vidicon
RADAP	Radar Data Processor (WSFO, Oklahoma City)
RFC	River Forecast Center
RGB	Red, Green, Blue
SAR	Synthetic Aperature Radar
SeaWifs	Sea-Viewing Wide Field of View Sensor (EOSAT)
SLAR	Side-Looking Airborne Radar
SPOT	System Probatoire d'Observation de la Terre
SSM/I	Special Sensor Microwave/Imager (DMSP)
SWIR	Short-Wave Infrared Radiometer (JERS)
TDRSS	Tracking and Data Relay Satellite System
TM	Thematic Mapper
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
VAS	Visible Spin Scan Radiometer and Atmospheric Sounder
VNR	Visible and Near-Infrared Radiometer (J-ERS)
VTIR	MOS-1's Visible and Thermal Infrared Radiometer
WES	Waterways Experiment Station (Corps of Engineers)
WSFO	Weather Forecast Offices

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In the last decade, significant new tools have become available for planners, managers and scientists working in hydrologic engineering. Two new and significant tools are the widespread availability of spaceborne multi-spectral remote sensing systems, and the development of more sophisticated and less expensive micro computer work stations for both image processing and spatial data (GIS) analyses. This paper describes an evaluation of emerging remote sensing and spatial data capabilities and applications performed for the Corps of Engineers Hydrologic Engineering Center at Davis, California. It first surveys recent and planned spaceborne remote sensing systems providing data relevant to the hydrologic community. Next, integraded digital image processing and Geographic Information Systems (GIS) available today on microcomputers for applied hydrologic analyses are reviewed. Finally, the interaction of these capabilities is examined in the context of specific hydrologic engineering and planning tasks, ranging from real-time flood forecasting, to urban watershed modeling, to snow cover, evaporation, and soil moisture estimation.

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